

Reimagining Agriculture with Perennial Crops

A Study on the Diffusion of Innovation and Soil Ecosystem
Services in the New Perennial Grain Kernza

Ett Nytt Jordbruk med Perenna Grödor: En Studie i
Innovationsspridning och Mark ekosystemtjänster i det Nya
Perenna Spannmålet Kernza

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Abstract

Perennial crops have been identified as a pathway to implement ecological intensification, which in extent could make agriculture more socio-economically and ecologically sustainable. This is a master thesis in Agroecology – a growing scientific discipline that aims to investigate problems in the food system using a holistic and transdisciplinary approach, incorporating and integrating both natural and social sciences to transform the food system. In this context, the present paper has focused on the initial steps of introducing the perennial grain crop Kernza to the United States, applying a systems perspective to integrate early knowledge from experimental farmers with research on plant-soil interactions, comparing the abundance of arbuscular mycorrhizal fungi (AMF) in a perennial settings with their annual monologues. In the first part of the paper, interviews with five experimental farmers across the US are analyzed using an innovation framework to gauge what motivated their choice to grow Kernza, and what other variables might have affected their decisions to adopt the crop at this early time. The results show that these growers represent a variety of typical farmer backgrounds with very different motivations for experimenting with the crop, including using it for its abilities to reduce weed-pressure, earn profits from a new and exciting crop, or to support researchers in developing these crops; where the most common reason to adopt and trial the crop was curiosity and interest in sustainability. It was shown that the most important attributes affecting the diffusion of new innovations like Kernza include their relative advantage, such as the economic benefits for the farmer, Kernza's soil-building capabilities, and that the complexity of growing the crop can be alleviated by improving the distribution of knowledge. This may be done by creating model farms where the current benefits of the crop can be put on display, and where economic performance in such a context can be highlighted for innovators and early adopters. Furthermore, the results show that these crops could be attractive and relatively easy to implement by farmers that already grow small grains, perennial seeds like lucerne, or otherwise have the knowledge, equipment and socio-economic means of growing a grain currently in development. But for the crop to reach its current potential, such plantings should consider using Kernza as a dual-purpose crop to make use of both seed and plant residues for forage, primarily on marginal lands that otherwise would not have generated any reasonable income. The second part of the thesis set out to analyze the abundance of AMF in a 3-yr Kernza field, a 1-yr Kernza field, a 1-yr Kernza-lucerne intercrop, and a field planted with winter wheat using PLFA and NLFA-analyses. The results show a significantly higher abundance of the NLFA 16:1 ω 5 indicative of AM hyphae in the oldest perennial cropping system at a soil depth of 30-60 cm, with similar but not significant differences visible at soil depths 0-5 cm and 5-30 cm. This was in line with the hypothesis that time between disturbance and the perennial nature of these crops should generate more abundant microbial communities than in crop agriculture dominated by high disturbance and annual crops. The implications of these findings are discussed, followed by suggestions for future research topics to enhance the understanding of perennial grains and perennial polycultures, and the interactions between these crops and the soil – innovations that holistically attempt to tackle numerous problems of agriculture at the same time. It is concluded that perennial crops have the potential to become a paradigm-shifting innovation capable of changing the mental models governing agriculture today: from high yields and high input systems reliant on annuals, to resilient farming systems where nature is the measure.

Foreword

My journey into the world of agroecology began more than four years ago when I spent several weeks pouring through Stephen Gliessman's *Agroecology – The Ecology of Sustainable Food Systems*, trying to wrap my head around how the food system worked, what its main challenges were, and in extent, what a new niche scientific discipline like agroecology could do about its problems. A mere six months later I found myself in a classroom with passionate people from all corners of the world, too seeking answers to the questions I posed – so we journeyed together. The group was composed of people from all walks of life, some with degrees in social sciences, others in natural sciences, with experience from farming in Sweden, Germany, Zimbabwe, Taiwan, and more. Collectively, we learned to utilize these differences, showing the immense power of diversity in thinking while discovering the true potential of transdisciplinary problem solving.

Fast forward two years, I find myself struggling to finding a topic for my masters' thesis. While I was convinced of the need for agroecology to become more mainstream to truly impact the way we produce and use food, I was overwhelmed with frustration that I could not find a way to achieve this in a reasonable time. And I was not alone. I think most of my classmates felt this frustration too, as we often discussed different ways to organize ourselves, to start companies or develop products that might at least make a dent in the food system.

Since then, the awareness of food and agriculture's contributions to climate change and ecosystem deterioration has increased considerably. Food waste is now a thing everyone talks about. Plant-based food companies are overturning very traditional markets, farmers are selling more and more directly to final consumers, interest in grass-fed beef is on the rise, and even large-scale meat companies are starting to invest in plant-based alternatives. But one of the most interesting developments of all, in my personal opinion, is the strides being made in the development of perennial crops: wheat, rice and oilseeds that can be grown for several years without being resown; innovations that exhibit the potential to disrupt the way we grow food completely, paving way for agroecosystems that mimic the natural ecosystems they displaced. These insights brought me to The Land Institute (TLI), a non-profit research institute based in Kansas – and the epicenter of development in perennial grains. TLI represents a strong vision to perennialize agriculture, a journey long in the making, with many years ahead of it still. But their work inspired me to learn more, eventually choosing to dedicate my master's thesis to perennial grains. More than two years later, here it is.

Acknowledgements

I started work on this thesis in the spring of 2017, aiming to finish some six months later with a clear intent on finding a job – then life happened. During the summer of the same year I was extremely fortunate to get the opportunity to visit the US, to see the Land Institute, and attend the annual Kernza conference to enrich my thesis – work that prolonged my work until the fall. Once home, I figured I would get a job and finish the thesis during evenings and weekends. Then life happened again, when our newborn son arrived 10 weeks premature, hospitalizing the whole family for months. Rising from that – finding inspiration, time and energy has been very challenging, especially when the paper had laid dormant for so long, with a lot of loose ends that needed to be reattached and understood anew. But here we are!

It's impossible for me to express enough gratitude to everyone who has helped me during this long process. But I'd like to direct a special thanks to my family for all their love and support, and to Hanna for always pushing and encouraging me, generating self-esteem on demand. Huge and eternal thanks go out to Linda-Maria, Ana and Sara, my super-awesome super supervisors. Your guidance has been key to all of this. I'm also eternally grateful for everyone who made my trip to the United States and Kansas possible, and all the amazing people we met along the way. This list is too long to include here, but a special thanks to Tim and Sarah and their families who gave us a roof over our heads, introduced us to burritos, let us sneak peek on their upcoming music performance, and for showing us around in Salina. I will treasure our experiences the rest of my life. I'd also like to send my thanks to Lee at TLI, and Dana at Plovgh for helping me find farmers to interview, as well as Ryan, Will, Agnetha and company at Biosystems and Technology at SLU Alnarp, who made me feel like an employee during my stay there. I'm also thankful for the chance opportunity to work with innovations and sustainability at SLU Holding for the past two years, where I have gotten the opportunity to learn firsthand how new ideas are shaped and turned into new products and services – lessons that have enriched my thesis tremendously.

My final shutout goes to the farmers who participated in my study, without you, this would not have been possible. I had a great time talking with you all, sharing jokes and laughs as I hesitantly made my way through my intricate interview guide.

I'd like to direct a special thanks to one of my respondents who said the following:

"Its people like you, with your deep interest who are really going to make this thing more and more successful. You've got the energy, time ahead of you to do it, and your creative ideas are just going to be a part of it, so I just want to thank you and people like you for making the effort to make it possible."

A quote that struck several chords in times of hardship. Thank *you* for your service – you, and the rest of the farming and research community are making these developments possible through your vision and hard work. Generations of visionaries and diligent do-gooders who hope that these ideas really come to fruition, aiding in this much needed transition from annual monocultures to perennial polycultures.

List of Acronyms

PLFA	Phospholipid Fatty Acid
NLFA	Neutral Lipid Fatty Acid
FAME	Fatty Acid Methyl Ester
PCR	Polymerase Chain Reaction
CLPP	Community Level Physiological Profiles
AM	Arbuscular Mycorrhiza
VAM	Vesicular Arbuscular Mycorrhiza
AMF	Arbuscular Mycorrhizal Fungi
CFU	Colony Forming Unit
ANOVA	Analysis of Variance
SAFE	SITES Agroecological Field Experiments
SITES	Swedish Infrastructure for Ecosystem Science
MB	Microbial Biomass
IWG	Intermediate Wheatgrass
DOI	Diffusion of Innovations

Word List

Innovator	First 2.5% of a population to adopt a new idea
Early adopter	Next 13.5% of a population to adopt an innovation
Early majority	34% of a population to adopt a new idea
Late majority	34% of a population, the next to final segment to adopt a new idea
Laggards	The final 16% to adopt an innovation
Trialing/Experimenting	Used interchangeably, reflecting field trials by farmers
Innovation adoption	Used to reflect the intention to use the crop in the foreseeable future

Organizations

Cascadian Farms	An organic food brand owned by General Mills
Patagonia Provisions	Clothing brand Patagonia's food division
Plovgh	Specialty crop buyer and seller in the US
The Land Institute	Non-profit research organization breeding perennial grains
Nordisk Råvara	Specialty crop seller, focusing on heritage- and innovative crops
Warbro Kvarn	Small scale miller, and specialty crop seller, focus on heritage grains

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1 Introduction

1.1 Agriculture – From Subsistence Farming to Industrial Production

Agriculture has gone through tremendous changes since its original inception more than 10,000 years ago (Zohary *et al.* 2012). Clearly one of the most influential innovations in human history, it allowed early humans to settle before eventually giving rise to the type of society humans enjoy today (Diamond & Bellwood 2003). Guided by human needs and beliefs, agriculture went through many iterations during this period, giving rise to innovations such as the maize, bean and squash intercrop mixture prevalent in the Americas, green manuring, agroforestry, among several others (Gliessman 2014). But starting in the 1940s, many of these methods were rapidly displaced with the onset of the “green revolution” (Patel 2012), the release of an innovation package meant to increase yields and maximize profits for farmers (Gliessman 2014). By use of mechanization and agrichemicals this new way to farm aimed to rationalize agriculture to create economies of scale with the goal to make food cheaper. Given the resemblance to factory production, this model of producing food has become known as industrial agriculture (Wezel *et al.* 2009), a system in which food is a commodity, and the resultant environmental damages unpaid externalities.

1.1.1 Problems of Industrial Agriculture

Since then, this practice of farming has played a key role in the degradation of ecosystems worldwide – with problems such as soil erosion, excess water use, emissions, water and air pollution, reductions in biodiversity and a whole range of social issues (Gliessman 2014). Soil cultivation – a practice meant to increase aeration and water permeability of soil, or to incorporate plant residues and combat weeds constitutes one of these problems. This practice has been shown to increase soil erosion rates to a level 10-100 times faster than soils naturally form (Montgomery 2007) – a situation worsened by the overuse of irrigation, which in and of itself is also unsustainable when slow-to replenish aquifers are used as water sources (Gliessman 2014). A third problem is the fact that soil cultivation also affects the movement of carbon from soils into the atmosphere, which effectively exacerbates climate change (Lal 2004). Although these tools have aided farmers in simplifying production, increasing yields and improving the quality of products since they were introduced (Gliessman 2014), their disadvantages are now becoming more apparent – opening the door for new ideas and solutions.

1.1.2 A Patchwork of Solutions

Efforts by researchers and practitioners to control some of these issues include reduced tillage practices (Liebig *et al.* 2004), cover-crops (Valkama *et al.* 2016), use of carefully planned crop rotations and long leys (Catt *et al.* 1998), biological nitrogen fixation (BNF) (Crews *et al.* 2005), intercropping and permanent landscape elements (Gliessman 2014). While others involve policies to support farmers for the ecosystem services they provide (Nelson *et al.* 2007). Together, several of these practices highlight the benefits of annual crops – which can complete their lifecycles within a short time period – particularly useful when planting cover crops – or when implementing crop rotation practices to break disease cycles. These patchwork solutions are necessary, but they are arguably only addressing the symptoms of an

even greater problem: the annual nature of our staple crops – and the cultivation practices they necessitate (Cox *et al.* 2004).

1.1.3 The Root of the Problem

These problems have persisted since the origins of agriculture, when humans domesticated annual rather than perennial plants (Zohary *et al.* 2012), primarily because they exhibited a higher productivity than did their perennial counterparts (Cox *et al.* 2006). But these actions effectively set the stage for a 10,000 year addiction to the plow and agricultural landscapes dominated by annual monocultures – landscapes that used to be primarily perennial and composed of plants grown in mixtures (Cox *et al.* 2010). This model of what used to be is now helping researchers forge new solutions for the future of agriculture that help solve many of the abovementioned issues at the same time; the development of perennial cereals, legumes and oilseed crops (Batello *et al.* 2013). The forerunning organization pushing for the development of these crops is the Land Institute (TLI), based in the United States – a non-profit research organization who envisions a future food system that draws inspiration from natural ecosystems. Their goal is to breed perennial crops for use in diverse polycultures capable of sponsoring their own fertility and pest protection, reducing the need for external inputs – a total reimagining of what it means to grow food on earth (Cox *et al.* 2004).

1.2 The Potential of Perennials

Perennial crops feature many advantages when compared with their annual counterparts, many of which can be attributed to the absence of soil disturbance and the presence of large root systems (Sprunger 2015). Some of these root systems are remarkable at intercepting soluble nutrients (Culman *et al.* 2013; Sprunger 2015), giving credence to the *safety-net hypothesis* of perennial roots (Allen *et al.* 2004) and their abilities to reduce leaching (Jungers *et al.* 2019). Such qualities could mean higher nutrient use efficiencies compared with annual crops, who only make use of ~30-50%, of applied N (Cassman *et al.* 2002), and ~41-45% of applied P (Smil 2000), which in effect may reduce the need for fertilization (Crews *et al.* 2005). But the large root systems of perennial crops have other benefits as well, including the ability to collect water in deeper soil layers during drought conditions (Kantar *et al.* 2016), and the potential to sequester carbon more efficiently than annuals do (Culman *et al.* 2013). Moreover, research has shown that these crops could also be very competitive with weeds, as in the case of Intermediate wheatgrass, or serve multiple functions on the farm, by producing both human-edible seed, and hay for livestock (Dick *et al.* 2018).

But the vision to develop these perennial crops in order to displace their more input-dependent annual counterparts has also been criticized, in for example “A Strong Perennial Vision – A Critical Review” by Smaje (2015). He argues, this vision can be divided into two parts: a weak perennial vision (WPV) and a strong perennial vision (SPV). Here, the WPV supports the idea of integrating perennial shrubs and trees, such as agroforestry practices into annual agriculture, while the SPV supports the replacement of annual agriculture with perennial grains completely. Smaje (2015). argues that the merits of SPV are not strong enough, citing that perennial crops that yield at an equal or higher level than current annual grains is impossible without losing the ecological benefits of perennality, or perennality itself. He does this by citing the C-S-R model of Grime, a conceptual tool that divides plants into different categories depending upon their survival strategies – where perennial crops

inevitably lose their competitive (C) and survivalist (S) attributes, i.e. deep roots and foliage if they are bred to increase seed yield, in effect becoming ruderals (R), just like their annual counterparts (Grime, 2012, see (Smaje 2015b)). He concludes that while perennial plants could contribute to a more sustainable food system, their contributions may be limited by their intrinsic biology, and as such, research should focus less upon the concept of perenniality itself, and more upon other solutions within agroecology.

This review has in turn been criticized by Crews & Dehaan (2015) in “A Strong Perennial Vision – A Response”, who highlight the issue of condemning perennial crops based on ecological theory that is only meant to describe different life histories of plants, not to predict the evolvability of new ones – including plants which could not have evolved, as the ecosystems allowing for their survival had not yet been invented: i.e. human managed perennial grain agroecosystems. They conclude that both visions have merits (i.e. WPV and SPV), reiterating the inherent problems of annual agriculture, whose plants always need to restart from seed every year, and stressing the necessity to develop perennials that circumvent these problems.

While it is too early to say whether the attempt to develop perennial grains will work in practice, research by DeHaan *et al.* (2018) showed no signs of perenniality being negatively affected by increased seed mass and yield over six breeding cycles. But other factors also speak in favor of the development of higher-yielding perennial crops, such as the extended cropping season, where roots and shoots of perennials will develop faster, and therefore produce more photosynthate than annuals, which need to regrow from seed every season (Cox *et al.* 2006).

1.2.1 Background Perennial Grains

Among all the perennial plants currently being researched and developed for crop production, Intermediate wheatgrass [*Thinopyrum intermedium* (Host.) Barkw. & D.R. Dewey] stands out as a prime candidate. With seeds slowly approaching the size and amount comparable with wheat, and flavors that have so far allowed for the production of both beers, bread and pasta, this “*proto crop*” offers eaters a novel food experience, sparking both interest and collaborations the world over, including partnerships between The Land Institute and Patagonia Provisions, and Cascadian Farms, a subsidiary of General Mills (The Land Institute 2019a)

The plant took its first steps towards domestication at the Rodale Institute in 1987, sparking a breeding program at the USDA Plant Materials Center in New York three years later (DeHaan *et al.* 2018). After years of falling interest, the programs were shut down by the year 2000, only to be reawakened a few years later at the Land Institute, when the plant was trademarked as Kernza, becoming one of several perennial grain candidates currently under development at the institute (The Land Institute 2019a)

By 2010, research focusing on perennial grains had been initiated by TLI, Australia’s Future Farm Industries Cooperative Research Centre, and the Yunnan Academy of Agricultural Sciences, as well as other smaller research groups. Together, these institutions have focused on breeding several different potential crops, including intermediate wheatgrass, perennial wheat, perennial sorghum, perennial sunflower, Maximillian sunflower, Illinois bundleflower, as well as perennial rice (Cox *et al.* 2010). But other promising candidates exist as well, such as a perennial variant of field cress (Batello *et al.* 2013). These crops are now being grown and developed on all continents of the world, excluding Antarctica (Crews & Cattani 2018), with

recent commercial scale US plantings of intermediate wheatgrass, supporting new products from Cascadian Farms (The Land Institute 2019a) and a 26 hectare (ha) large field in southern Sweden (Dagens Industri 2019).

Intermediate wheatgrass, henceforth referred to as Kernza has received a lot of interest since its relative reawakening in the early 2000s. During this period most of the research surrounding the crop has naturally focused on plant breeding, such as increasing grain yield and shatter resistance (Cox *et al.* 2010) and accelerating domestication (Zhang *et al.* 2016). This is accompanied by a growing body of research on the agronomics of Kernza, including crop establishment (Schmer *et al.* 2017), how grain and forage yields are affected by nitrogen fertilization (Jungers *et al.* 2017), the possibilities of intercropping (Dick *et al.* 2018), and the possibilities of harvesting both seed and forage (Pugliese *et al.* 2019).

These studies have proven important, as more and more farmers have begun to experiment with Kernza and other perennial grains, which in turn has allowed researchers an opportunity to better understand the practical experience farmers of growing the crops (Lanker *et al.* 2019). Other important research areas include the potential ecosystem benefits of perennial crops, including the potential of perennials to reduce leaching (Culman *et al.* 2013; Jungers *et al.* 2017, 2019).

However, few studies have so far sought to understand the below ground interactions between the roots and the soil microbiome in Kernza, an area of increasing interest considering the potential benefits of BNF through plant-bacteria interactions, or the potential symbiosis between plants and mycorrhizal fungi which could aid the plant in both water and nutrient uptake. Likewise, very little research exists on the socio-economic aspects of growing perennial crops, such as the motivations and expectations of potential growers, or the process of releasing these crops to a wider audience.

1.2.2 New Research Opportunities

Given the multiple issues of industrial agriculture, especially those that relate to leaching, erosion and loss of soil carbon, the promises of perennial plants are becoming more and more alluring, as these have shown to mitigate or even reverse several of these issues. This has inspired organizations like the Land Institute, companies like Patagonia Provisions, and universities all over the world to accelerate research into these crops; researching and developing crops that may be planted by ordinary farmers as soon as possible (The Land Institute 2019a). In the case of Kernza, this is quickly becoming a reality, as The Land Institute is looking to release the crop to a wider audience in the upcoming years. This pursuit, along the ambition to develop other perennial crops alongside Kernza, has spurred projects and global partnerships at several of the worlds' leading research institutions, including the University of Kansas, MIT, Cornell University and Yunnan University in China, to name a few. In Europe, these are joined by the Swedish University of Agricultural Sciences in Alnarp and Uppsala, whose research revolves around ecosystem science in perennial grain cropping systems, plant breeding, respectively; in turn accompanied by Lund University in southern Sweden, who takes a broader view, with a research focus on the social and natural science aspects of perennial grains. Other initiatives involve the DeepFrontier project at the University of Copenhagen in Denmark who study the root ecology of deep rooted agricultural plants, or the Perennial Grains Research Project at ISARA-Lyon in France, who aims to test the value of perennial grain crops and their multipurpose aspects at multiple sites (The Land Institute, 2019b). But a lot of research remains to be done, especially within the realm of the

microbiome, the social sciences, encompassing economic benefits and the variables affecting how innovations are spread in society. This is where this thesis picks up, aiming to investigate both the social aspects of Kernza and its approaching market release, while simultaneously delving deep into the realm of the microbiome, in an attempt to shed light on some of the lesser known ecosystem benefits of these newly developed perennial plants.

1.2.3 Innovation Research: The Diffusion of Agroecological Innovations

Some of the earliest forms of innovation research focused on agriculture and the adoption of new agricultural practices among farmers, especially during the green revolution (Rogers 2003). But today there is also a growing body of research focusing on the diffusion of innovations that may be defined as agroecological practices. Examples of this include research from south America, where innovations with roots in traditional farming systems spread via *campesino a campesino* (farmer to farmer) networks (Altieri *et al.* 2015), the diffusion of ideas such as no-till conservation agriculture (Lestrelin *et al.* 2012) or certified organic production (Padel 2001).

Adebiyi *et al.* (2016) refers to these ideas and practices as transformative or radical innovations – ideas that force us to rethink how things work, giving rise to new mental models of how for example food production can take place (Rogers 2003). According to Adebiyi *et al.* (2016), perennial grains could become such a transformative technology – if their development and widespread adoption succeeds. In their study, they interviewed farmers interested in perennial grains *ex ante*, farmers who at the time had not yet tried growing perennial grain crops. They wanted to understand what characteristics and uses might interest future potential growers, which in turn could influence the direction of breeding and domestication. This study was conducted in the US, but a similar study has also been carried out in Sweden by Marquardt *et al.* (2016). Both studies conclude that there is an interest in these crops, especially when used as a dual-purpose crop to produce both food for humans and feed for animals, or when used on marginal lands which currently may not generate a significant income. Other farmers highlight the opportunity to earn an income by selling the seed as a niche crop using shorter value chains. On the negative side, some farmers may fear that the crop will become hard to terminate, in effect becoming a weed. These studies are based on research showing the long-term effects and potential of these crops, including the possibilities to reduce on-farm inputs and costs. In 2008, these prospects inspired Bell *et al.* (2008) to develop a model conducting a whole-farm economic analysis of perennial grains in an Australian dryland farming system. Although preliminary at the time, their analysis showed that dual-purpose perennial cropping systems could be competitive with their annual counterparts, if both food and feed are produced on site. Although this study was primarily focused on perennial wheat, more than ten years have passed, during which time the seed yield of several perennial candidates have seen tremendous progress. This makes the prospect of releasing perennial crops on a wider market in the near future very enticing, despite their current shortcomings.

However, at the time of writing, only one study has so far examined the early experiences and motivations of producers actually trialing Kernza (Lanker *et al.* 2019). They found that current Kernza producers mainly grow the plant for use as a forage crop, and when applicable, enjoy the benefits of harvesting both forage and seed, or for its ecosystem services – a result of several agronomic uncertainties tied to the novel crop. These uncertainties include planting

timing, lowering of yields over time, as well as economic and market related concerns, issues that need to be resolved as the crop now moves into a commercialization phase.

Together, these experiences represent important cues to stakeholders developing perennial crops, but they may also be used to guide the commercialization efforts of said crops. To accelerate this process, the present study employs a similar approach to that of Lanker *et al.* (2019), but in addition also applies an innovation framework to better understand what variables affect the adoption of these innovations by early Kernza growers.

Understanding these variables is important when devising future research and planning the scale-up and diffusion process of agroecological innovations like perennial grains. Understanding these underlying variables is also highly relevant when considering recent large scale plantings of Kernza, such as the 2018, 26-ha field in Sweden (*Dagens Industri* 2019), a venture whose outcome could affect the future adoption of the crop.

1.2.4 Soil Ecology Research: Microbial Communities – Annuals vs Perennials

Another research area that has received little appreciation within the field of agriculture is that of soil ecology – the study of soils, their processes and the life they contain. These ecosystems exist within the matrix of mineral materials, organic matter, gases and water that we call soil (Bardgett 2005). The earth's soils are full of highly diverse life, with estimates that a single gram of soil may contain as much as 1 billion bacteria from tens of thousands of different taxa, close to 200 meters of fungal hyphae, as well as a variety of both nematodes, mites, earthworms and arthropods (Bardgett 2005; Wagg *et al.* 2014). Together, these organisms form the soil food web, a collection of different biota that contribute to human essential ecosystem services such as food production, nutrient cycling and climate mitigation (De Vries *et al.* 2013).

However, recent studies suggest that these ecosystem services may be under threat as a result of anthropogenic activities such as intensive farming (Wagg *et al.* 2014). These activities have been shown to reduce the amount of organic matter in soil, as well as the biomass of most soil microorganisms. This in turn has led to a shift in the microbial communities of intensively managed soils, which have become more dominated by bacteria. The implications of this shift includes higher rates of nitrogen leaching, and carbon sequestration rates that are far lower than in less intensively managed soils (De Vries *et al.* 2013).

By developing and growing perennial grain crops, researchers are attempting to find out if these plants can solve several of these issues at the same time; with a lot of focus on the soil-root interactions of perennial crops. This research builds upon results from previous studies that highlight the importance of roots in building more stable soil organic C pools (Kätterer *et al.* 2011; Sprunger *et al.* 2019a); or the positive effects of permanent soil cover and minimal soil disturbance on soil erosion (Montgomery 2007), macro aggregate soil structure, carbon sequestration, microbial biomass, and overall soil ecosystem functioning (Vezzani *et al.* 2018).

But little research has so far been done to increase understanding of how these plants interact with the soil microbiome; especially with regard to organisms that help plants access nutrients and water more efficiently – functions that will become increasingly important in light of climate change.

An especially important group of these microorganisms consist of the mycorrhizal-forming fungi – microorganisms that can enter into symbiosis, *mycorrhizae* with most land plants (Hodge 2000; van der Heijden 2010), allowing for the bi-directional transfer of energy and

nutrients between fungi and plant (Bardgett 2005), as well as granting affected plants improved defenses, drought resistance, while simultaneously improving soil aggregate stability (Hodge 2000). These fungi act as an extension of the plant's root system, increasing coverage in the soil profile, aiding in the capture of several essential plant nutrients (Clark & Zeto 2000). Together they constitute a highly diverse group of microorganisms, with three distinct groups: ericoid mycorrhiza, ectomycorrhiza and arbuscular mycorrhizal fungi (AMF), the latter of which is implicated in up to 80% of all plant-fungi associations (Lambers *et al.* 2008) – and the primary group of interest in this thesis. These organisms belong to the division Glomeromycota, a group of fungi that form intricate intracellular fungal structures called *arbuscules*, sites where the exchange of phosphate between fungi and plant is believed to take place (Hodge 2000).

AMF are important to ecosystem functioning, but some researchers argue that their positive benefits in agriculture are overstated. Ryan & Graham (2018) reviewed several meta-studies centered on mycorrhizal contributions to crop productivity, finding that the underlying materials used did not represent actual crop production fairly – therefore overestimating the need to manage for AMF. In one of the studies in their review perennial plants had been used to exemplify the positive effects of mycorrhizae, a decision criticized by Ryan & Graham (2018) who deemed perennial plants to be irrelevant in broad acre agriculture. But research has shown that mycorrhizae could play a vital role in reducing leaching in perennial grasslands (van der Heijden 2010), aiding in capture and redistribution of insoluble inorganic phosphorus in soil (Clark & Zeto 2000; Tawaraya *et al.* 2006), or enhancing the BNF of legumes, as implied in research by Redecker *et al.* (1997) and shown in tall grass prairie restoration research by Larimer *et al.* (2014).

These findings serve to highlight the discrepancy between annual and perennial agriculture, and the need to better understand the plant-soil interactions of both systems. But if the positive effects of perenniality and their potential cooperation with different microbial communities are proven accurate, they also offer opportunities to develop new innovations, not only based on the perennial traits of new crops, but also on the ecosystem services and functions delivered by different soil microbes and their respective communities (Chaparro *et al.* 2012). Two examples of this includes research by Middleton *et al.* (2015) who demonstrated improved plant vigor and herbivore resistance in plants inoculated by locally adapted AMF, as well as research by Koziol & Bever (2017) who showed that a similar approach could accelerate succession in restored grasslands.

Zooming in on perennial grains, very little research has been done to investigate how these results pertain to a *proto crop* like Kernza. But in one study, Sprunger *et al.* (2019b) showed that Kernza grown for four years saw its soil food web complexity increase when compared with a similar system featuring annual wheat. This study highlights that it may take time for an agroecosystem to move from a state that only carries annuals, to one where the disturbance regime ends, paving way for a perennial agroecosystem further down the successional gradient (Crews *et al.* 2016); a state where the benefits of a perennial cropping system becomes more apparent.

1.2.5 Soil Ecology Research: Arbuscular Mycorrhiza Abundance

Considering the potential positive effects of AMF on agroecosystems, the second part of this thesis sets out to conduct the first study determining the abundance of AMF in different

agroecosystems featuring Kernza, to compare these with an annual reference system with winter wheat.

In previous research, perennial agroecosystems have been shown to host more AMF compared to cropland dominated by annual production (Allison *et al.* 2005); mirroring the results of other studies that link reduced- or no-till agriculture to an increase in AMF abundance (Kabir *et al.* 1997; van Groenigen *et al.* 2010). This hints at a strong relationship between soil disturbance and AMF; suggesting that perennial agroecosystems could be more abundant in AMF than their annual monologues, in part as a result of reduced disturbance, but also because of their extensive root systems which may be active year-round. Speculating further, it may also be argued that the perennial agroecosystem could have more AMF at deeper soil depths when compared with annual wheat. This builds upon work by Sprunger (2015), who showed that a crop of three-year old Kernza produced significantly higher levels of root biomass down to a depth of 40 cm when compared with wheat, roots that could be associated with AMF, as in the case of *Thinopyrum ponticum* (Covacevich & Echeverría 2009) a close relative of the undomesticated Kernza [*Thinopyrum intermedium* (Host.) Barkw. & D.R. Dewey]. Meanwhile, previous research has shown that diazotrophs (nitrogen fixating bacteria and archaea), could stimulate the development of mycorrhiza (Garbaye 1994; Duchene *et al.* 2017) creating opportunities for resource exchange between the plant, fungi and bacteria in a tripartite symbiosis. These exchanges could be essential for the plant and bacteria in agroecosystems low in readily available P, an essential nutrient in the BNF process, which in turn could affect the N availability to the plant and the agroecosystem as a whole: issues that may be alleviated by AM fungi that have better access to soil P, and have been shown to stimulate BNF in research (Püschel *et al.* 2017). Although context dependent, these results raise the question whether a Kernza-lucerne intercrop may host a higher abundance of AMF than its sole-cropped counterpart.

1.2.6 Aims

The overarching aims of this thesis has been to investigate, compare and discuss the socio-economic and environmental aspects of annual and perennial cropping systems. The following research questions and hypotheses have served as guidelines in this pursuit.

Research Questions: Variables Affecting the Diffusion of Perennial Crops

In the social science part of the thesis, this is achieved by interviewing farmers experimenting with Kernza, and analyzing their responses through the lens of an innovation framework.

- What underlying motivations guide farmers to experiment with a new crop like Kernza?
- What characterizes the initial stages of Kernza's innovation diffusion process?
- What variables affect the adoption and diffusion of this innovation?
- What can be done to accelerate the adoption- and diffusion process of perennial crops?

Hypotheses: Annuals vs Perennials – Comparing Soil Microbial Communities

In the natural science part of this thesis the total biomass of AMF in four different agroecosystems was estimated at a depth ranging from 0-5, 5-30, 30-60 and 60-90 cm. This

was done by analyzing the phospholipid and neutral lipid fatty acids 16:1 ω 5 indicative of mycorrhizal fungi in four different agroecosystems. They include a: three-year Kernza, one-year Kernza, one-year Kernza and lucerne intercrop, and a one-year old annual winter wheat system. Building upon the arguments on the previous page, it is hypothesized that:

- AMF should be more abundant in the perennial agroecosystems compared with wheat, stemming from the absence of soil disturbance over time and the presence of an extensive, presumed active root system, with a higher abundance in the three-year old Kernza system, followed in decreasing order by the one-year Kernza systems, and the annual wheat system.
- There will be more AMF in the deeper soil layers (>30 cm) following the gradient three-year Kernza, one-year Kernza and lucerne intercrop, one-year Kernza, and lastly, the one-year annual winter wheat, as a result of time without disturbance, and the downward extension of Kernza's root system over time.
- The presence of a legume intercrop may stimulate the development of mycorrhizae in the Kernza and Lucerne biculture, which in turn could generate a higher abundance of AMF as compared with the 1-year Kernza as a sole crop.

2 Theories and Concepts

Several theories and concepts have been used to unite the socio-economical and natural science parts of this thesis. These include the concepts of agroecology, systems thinking and ecological intensification, as well as basic innovation theory, which will be used to analyze and discuss the results of the interview study.

2.1 Agroecology

Many attempts have been made to define agroecology as a concept. Historically, some have referred to it as the ecological study of agroecosystems, while others see it as the marriage of agriculture and ecology (Francis *et al.* 2003a). However, since its initial use in the literature in 1928, agroecology has become more than the scientific inquiry of ecological functions in agroecosystems (Gliessman 2014). The term now also represents a collection of underlying farming practices – tested by time, indigenous people and the scientific community – shown to be more sustainable than many of the conventional techniques used in agriculture today; along with the socio-political movement of agroecology – the right for peasant farmers to land, seed and food (Wezel *et al.* 2009). Francis *et al.*, (2003, p. 100) gives the following more wide-spanning definition of the concept, focusing on the science part of agroecology:

“We define agroecology as the integrative study of the ecology of the entire food system, encompassing ecological, economic and social dimensions.”

Together, these three dimensions of agroecology can be seen as the collective endeavor to create more sustainable farming systems by constant inquiry, and by combining indigenous knowledge and lessons of the past with contemporary ideas and innovations. At one end of the spectrum, this may translate into the diffusion and adoption of more sustainable farming practices among farmers, but on the other end it also translates into a deeper understanding

of how agroecosystems function, and how current practices are currently undermining the very foundations upon which our food production relies (Gliessman 2014).

To address these issues (Gliessman 2014) has developed a framework to assess the progress of individual farms and the food system as a whole in the attempt to achieve sustainability. The levels of conversion describe the transition from a food system locked in the industrial model to a global food system that transcends the needs of the conversion ladder in the first place, a global and sustainable food system; where levels 1 through 3 describes the practices and structures at the farm level, and 4 through 5 the food system itself. According to Gliessman (2014), level 1 describes a food system primarily focused on efficiency, level 2 input substitution, where synthetic inputs are substituted with their organic equivalents, whereas level 3 revolves around the complete redesign of the agroecosystem. By relying on a new set of ecological processes, in theory, systems at level 3 should be able to avoid many of the problems at levels 1-2 completely, rather than requiring the farm manager to find short term solutions to typical farming problems on a regular basis. At this level, agroforestry practices, similar in their life histories to that of perennial grains, multiple cropping systems and rotations serve as examples of agroecosystem redesign.

Meanwhile, level 4 describes the reestablishment of a direct connection between grower and eater, where the grower has an opportunity to support farmers going through the process of transition towards level 3, acting as an enabler by buying products from producers in transition; a process further intensified at level 5, where the transition towards level 3 and 4 continues at a global level, deeply affecting the very nature of human civilization.

Instead of continuing to develop new innovations and practices for levels 1-2, some researchers argue that we need to shift the paradigm completely, not simply substituting harmful agricultural practices with more benign alternatives (Rosset & Altieri 1997), instead arguing the need to completely redesign our agroecosystems from the ground up (Krupnik *et al.* 2003; Gliessman 2014). A transition that is just, economically viable and ecologically sound. One recently popularized idea that might in part achieve this, is to incorporate lessons from ecology in the redesign of agroecosystems; employing the power of diversity by growing several crops in polycultures or mixtures (Altieri *et al.* 2017a), replacing annual plants with perennials, creating ecosystems further down the successional gradient (Crews *et al.* 2016), and by combining crop and animal agriculture in mixed systems (Altieri *et al.* 2017b) - the very theme of this thesis.

2.2 Ecological Succession

Ecological succession is broad term commonly used in describing the change in composition of biological communities and their related ecosystem processes over time (Odum 1969, see Crews *et al.* 2016). This change may be divided into several phases, such as primary succession, when different organisms colonize parent materials for the first time, or secondary succession, which may take place after a pre-existing ecosystem is disturbed by for example a fire or a flood (Whittaker 1975, see Crews *et al.* 2016). These disturbances can have short, but also long-lasting negative effects, such as soil erosion (Montgomery 2007), or eutrophication (Rabalais *et al.* 2002); both in natural ecosystems, but also in and from ecosystems managed by humans – where their effects may be more apparent. While natural ecosystems recuperate after such disturbances through colonization by annuals, and eventually by perennials when nitrogen is limiting (McClendon & Redente 1992), this process is stalled in agricultural ecosystems, leading to many of the environmental problems already described. According to

Crews *et al.* (2016) most of our agroecosystems are currently arrested at this retro-successional stage, where human actions keep “resetting” the agroecosystem to only harbor annual plants every year; a process which does not exist in natural ecosystems. Instead of resisting this change, several researchers now suggest that we should incorporate the concept of succession into agriculture, by for example developing perennial crops that mimic the natural perennial communities that dominate many landscapes of the Earth (Crews *et al.* 2016).

2.3 Ecological Intensification

Ecological intensification is an agroecological concept describing how agroecosystems can be shaped to produce food with less resources (Bommarco *et al.* 2013; Crews *et al.* 2016). This idea takes inspiration from nature, incorporating systems thinking and recognizes that agroecosystems could function in a more sustainable way if they relied less on anthropogenic inputs, and more on ecosystem services provided by below and aboveground organisms (Bommarco *et al.* 2013). These organisms can provide both supporting (such as soil formation and nutrient cycling) and regulating ecosystem services (e.g. biological pest control, pollination, climate regulation and water purification) while simultaneously offering human societies provisioning services – the food-, fuel and fiber products we physically grow. But rather than only planning for spatial diversity to increase the use of these services, the necessity to increase diversity in time has become more and more apparent. This is already done to a large degree by farmers practicing crop rotations (Gliessman 2014), but according to some researchers ecological intensification could take this practice to a new level by also including the concept of succession in the design of agroecosystems (Crews *et al.* 2016).

So far, this approach has largely only been possible in the tropical regions of the world, where farmers employing agroforestry methods (production of tree crops) are more common. But with the advent of perennial grain crops, this framework is now becoming more relevant in other parts of the world as well.

2.4 Systems Thinking

Agroecology represents a holistic approach to the implementation of sustainable food production on a global scale (Francis *et al.* 2003a). Systems thinking plays an integral role in this pursuit when applied to the complex world of food production and its ecological, economic and social dimensions; opposing the more traditional, reductionist view otherwise prevalent in agricultural research (Bawden 1991). Systems thinking is commonly divided into a “soft” and “hard” part, describing different methods in which the complexity of different problems can be broken down and better understood as a whole (Checkland 2000). Proponents of the “hard” paradigm of systems thinking perceives of the world as a series of interconnected systems, which – if not functioning properly, can be reengineered to do so. This paradigm can be used to define and study the boundaries of an agroecosystem, how food is distributed in a local community, or how multinational corporations interact on the global market. Meanwhile, the “soft” systems approach takes a radically different stance – focusing more on the process of learning about the problems themselves, highlighting the potential for change by iterative learning processes (Checkland 2000).

In this thesis the hard systems approach was applied when discussing problems of individual agroecosystems and how these are connected to other systems such as global

biogeochemical cycles or marine ecosystems suffering from eutrophication, while the soft paradigm was used when discussing agricultural issues that are, at current, mostly being treated using short term solutions rather than through efforts targeted at the root causes of problems.

2.5 Innovation Theory

In order to better understand the process of developing and releasing a new agricultural innovation such as Kernza, the innovation adoption/diffusion model described in (Rogers 2003) was used to analyze the results from the farmer interviews, focusing on the variables that affect adoption. This framework has been adapted to agricultural innovations on several occasions, including work by Guerin & Guerin (1994) who reviewed the adoption of innovations in agricultural research and environmental management focusing on barriers to adoption. They define seven key constraints to the adoption of new ideas: i.e. complexity, observability, cost, farmer's opinions toward the technology in question, level of motivation, relevance and attitudes towards risk and change. Variables similar to those highlighted in (Rogers 2003). In another case, Padel (2001) reviews the applicability of the adoption/diffusion model to predict the adoption of organic agriculture. She shows that the model could be used to define adopters along the adopter-category continuum and to discuss the complexity of the adoption decision; but cautions that organic agriculture in many ways does not resemble the typical innovation.

Rather than being an easily definable product whose benefits and potential risks are easily observable – key attributes that positively affect adoption (Rogers 2003), organic agriculture requires the adopter to completely rethink his or her values, restructure the farm and learn new skills – a complete system change fraught with high risk (Padel 2001). The act of adopting such an innovation is further compounded by societal forces such as the development of markets, attitudes among other members of a system, policy-support and more. This situation is bound to share a lot of parallels with the introduction of perennial grains and polycultures – innovations that may see similar challenges as they become more available on the market.

2.5.1 Innovation vs Invention

The terms innovation and invention are sometimes used interchangeably as synonymous with new ideas, products or services, or to explain the processes of developing new ideas, but in innovation theory they mean different things. Rogers (2003) defines innovation as an idea, practice or object that an individual may perceive of as new, regardless of how novel it is. But both innovation and invention can be used to explain the actual process of developing new ideas as well. According to Tidd *et al.* (2005) both of these concepts are part of a lengthy process where invention marks the conceptualization of a new ideas, whereas innovation is the process of bringing those ideas into widespread use, making them work in a desirable manner, both technically and commercially. In their definition, the concept of innovation is almost synonymous with the concept of change.

2.5.2 Different Types of Innovations

Innovation is a broad concept encompassing various types of processes. Tidd *et al.* (2005) divides this concept into four different categories called the 4P's of innovation, namely:

‘product innovation’, ‘process innovation’, ‘position innovation’ and ‘paradigm innovation’. In this case product innovation stands for changes in the product or services an organization may offer, while process innovation includes changes in the ways these things are produced and delivered. Position refers to the way the products or services are introduced and marketed to potential customers, focusing on steering perception, while the broad term paradigm innovation describes a change in the mental models which frame what a company or organization does.

2.5.3 Degrees of Novelty

Not all innovations are created equally: some exhibit higher degrees of novelty than others, where change may take place at either a component level, or at a systems level (Tidd *et al.* 2005). An example of this could be small updates to the composition of a product, to the introduction of new components, or – at the end of the spectrum, new materials that significantly improves the performance of the products’ components. Innovations at the systems level follow a similar continuum, where small incremental improvements could be likened to new versions of a car, whereas more radical innovations could be exemplified with the shift from cassette-music to CDs and MP3s. These changes are sometimes more or less bound to specific sectors, while sometimes they are so radical, they have the potential to change society completely, as happened during the industrial revolution with the invention of steam power, or the more recent revolution of Internet Technology. But these disruptions are rare, as most innovations happen incrementally, when new knowledge is incorporated to improve and develop a product or process.

2.5.4 Adopter Categories and the Diffusion of Innovations

The most commonly used method of categorizing adopters of new ideas was developed by Everett Rogers, reaching a broad audience when released in his 1962 book “Diffusion of Innovations, followed by its revised fifth edition more than 40 years later (Rogers 2003). Rogers theory of diffusion of innovations (DOI) has been applied in technology acceptance and sustainability evaluations (Aizstrauta *et al.* 2015), studies on the diffusion of solar panels (Wolske *et al.* 2017), diffusion of new ideas in health and service organizations, as well as practices relating to organic food production (Padel 2001) and more. In a part of DOI theory, adopters of new technologies are divided into five major categories depending upon innovativeness among the individuals within a social system, where the comparatively early adopters may fall under “innovators” to “early adopters” whereas the last individuals or groups to adopt an innovation may be categorized as “laggards.” This categorization model is based on real world observations used to create “ideal types” of adopters, which in turn makes comparisons possible. Together, these individuals, and the categories they fall under, help researchers and organizations better understand how new ideas take root, and spread in society.

The Innovators

According to Rogers (2003), the innovators make up approximately 2.5% of all potential adopters of a new idea. These exhibit an almost obsessive interest in ventures, which often leads to an exploration beyond the local peer networks, into more cosmopolitan circles. Their communication patterns and friendships exhibit similar patterns, as these individuals often

find new contacts among innovators that may be living very far away. Individuals that fall into this category may be affluent, which helps in absorbing potential losses from unprofitable innovations. But the innovator must also be able to cope with an increased level of uncertainty and be able to understand and apply technical knowledge. These individuals are often risk takers, which in turn entails accepting occasional setbacks when new ideas don't turn out the way they expect.

The Innovators play an important role in the diffusion of new ideas, such as when a new idea is imported from one social system into another; where the innovator gets to play the role of a gatekeeper, normalizing a new, unfamiliar idea among other potential adopters.

The Early Adopters

The next group of individuals to adopt an innovation constitutes the early adopter; a group of individuals, more driven by earning respect in their local communities, than building and maintaining networks with other innovators (Rogers 2003). This group makes up around 13.5% of the potential adopters in a system and plays a key part in normalizing an innovation further, by being closer to the average individual/adopter in terms of innovativeness, and by being more integrated in their local community. These individuals may serve as role models, harboring the highest form of opinion and thought leadership in most systems, which makes them the ideal local missionary for a change agent seeking to diffuse an innovation quickly. In a sense, the early adopter more or less puts his or her stamp of approval on a new innovation by adopting it, which in turn helps trigger a critical mass to adopt the innovation.

Early- to Late Majority and Laggards

Following tightly behind the early adopter comes the early majority making up 34% of all potential adopters in a system. These act at the interface between the innovators and the late adopters-laggards, rarely taking a lead themselves, but when they do, affect many potential adopters through their interpersonal networks. These include the late majority (34%) and the laggards (16%) – the former acting as a polar opposite to the early majority, characterized by skepticism, while the latter might could be best described as near isolates in the networks of their respective social systems (Rogers 2003). Together, these can be placed on a continuum of potential adopters, ranging from individuals and groups very eager, and able to make use of new ideas, to individuals who may harbor strong suspicions towards new technologies and innovations; feelings that shape intention, making the likelihood of innovation adoption much lower at the level of the laggard, as compared with the innovator or early adopter.

2.5.5 The Adoption Process

According to Rogers (2003), the decision to adopt a new idea can be explained in a five-stage innovation-decision process, a framework that simplifies the complex reality of innovation adoption. This process may begin with an individual seeking knowledge of an innovation, before going through a persuasion stage that either ends with a decision to adopt or reject a new idea, see it implemented, before eventually confirming whether or not the decision to adopt was right or wrong – a process in turn affected by different variables.

2.5.6 Variables Affecting the Rate of Adoption

Several variables affect the rate at which a new idea takes hold and spreads within a social system. Among these, the perceived attributes of an innovation seems to play a dominant role, accounting for 49 to 87 percent of all variance in the rate of adoption of new ideas (Rogers 1995). These include the relative advantage of said innovation, its complexity, trialability, observability, and finally, how compatible it is with the needs of a potential adopter. Other important variables include the type of innovation-decision an adopter must go through, the channels used to communicate information about an innovation, the extent to which an innovation is promoted, as well as the nature of the social system in which the adopter and innovation is embedded – which includes prevailing norms and the degree of interconnectedness of the system.

Relative Advantage

According to Rogers (2003) relative advantage appears to be one of the strongest predictors of how quickly a new idea will be adopted. The relative advantage of an innovation is the degree to which it may be perceived as better than the idea it may replace. These advantages can include the initial cost of purchase, how profitable it is to own and use, the degree to which it decreases discomfort, if it saves the user time and effort, and in many cases how much social prestige they grant their users. But sometimes the relative advantage of an innovation is hard to perceive, such as when the desired consequence guiding adoption is distant in time, or otherwise delayed.

Preventive Innovations

Some innovations grant the adopter its desired outcomes in near time, whereas others require the user to wait. This category includes preventive innovations, which a user may adopt in order to decrease the probability of a future unwanted event; by for instance changing lifestyles, including diet and exercise habits in order to reduce the likelihood of sickness in the future (Rogers 2003). These preventative innovations exhibit a much slower rate of adoption compared with innovations granting the user immediate results, owing to the complexity in perceiving their relative advantages.

The Effects of Incentives

Incentives can play a major role in speeding up the diffusion and adoption of innovations by acting as an enhancer of the relative advantage of a new idea (Rogers 2003). These may be monetary or consist of a gift of some sort, given to individuals or groups meant to stimulate behavioral change, such as the adoption of a new idea. These incentives can be given to potential adopters, in which case they are called *adopter incentives*, or to a diffuser, a recruiter (individual or company) who is rewarded by helping persuade potential adopters to take the leap, in which case it is called a *diffuser incentive*. Other types of incentives can be directed towards individuals, whereas sometimes they target groups of individuals, who can then inspire each other to adopt a new idea. Some incentives are paid out at the moment of adoption, whereas others can be awarded at a later stage. Apart from this, incentives can be both *positive* and *negative*, meaning that some reward an individual for adopting a new idea, while some penalize individuals for non-adoption.

Rogers (1973) draws the following conclusions regarding the effects of incentives, see (Rogers 2003):

1. *Incentives increase the rate at which innovations are adopted.*
2. *Adopter incentives encourage different types of individuals to adopt a new idea; individuals who may not otherwise have taken the leap because of for example socio-economic status.*
3. *Incentives may increase the quantity of adopters, but not necessarily the quality; in some cases, encouraging individuals seeking to take advantage of the incentive, only to discontinue using the innovation earlier than someone who wanted or needed it more.*

Complexity

Whereas some innovations are relatively simple to use, others may be much more difficult to understand and implement. For potential adopters struggling with such complexity, Rogers (2003) suggests a negative correlation with adoption rate – something he chooses to exemplify with the early history of home computers; when technologically knowledgeable individuals would adopt and use a PC with little trouble, whereas a later adopter with a less technological background would struggle to understand the hardware and software, the manuals, and even employees working with support.

Trialability

Trialability is the degree to which a potential adopter may experiment with a new idea before continuing through the innovation-decision process (Rogers 2003). Innovations that can be tried by the user allow potential adopters to see whether the idea works under their circumstances, which in some cases could lead to re-invention, where the innovation is essentially changed even before it is implemented in full scale. Taken together this has shown to increase the rate of adoption compared with innovations that cannot be divided for a trial, or that do not allow for a trial at all. In this case, Rogers (2003) suggests a positive correlation between trialability and an increase in rate of adoption; but also notes that this may be more important among early adopters than later adopters and laggards, referencing research by Gross 1942 and Ryan 1948. This may be due to the fact that later adopters have more information about the product, as the early adopters have essentially already trialed the innovation for them.

Observability

Observability can be described as the degree to which individuals may gauge the results of an innovation. Observability can be high; something (Rogers 2003) posits will increase adoption, but it may also be low and hard to communicate to others, which instead may lead to a slow rate of adoption.

Compatibility

Compatibility describes to what degree an idea is perceived as consistent with the existing socio-cultural values, past experiences or previously introduced ideas, and the needs of individuals within a social system (Rogers 2003). Innovations that meet these criteria help potential adopters by rooting the idea within the fabric of something familiar, which in turn reduces the amount of uncertainty an individual may hold towards a new idea. But the reverse is also true. Incompatible values can block or slow the adoption of an innovation – such as when American farmers who value increasing farm production may choose to avoid the adoption of soil conservation practices, as these may appear to be in conflict. This also holds true when replacing an old idea with something new – where compatibility with the old idea may either promote or slow down adoption.

Rogers (2003) states that old ideas act as mental tools that can be used to assess and give new ideas meaning, arguing that individuals can not relate to innovation other than by comparing them with what they have experienced in the past. New ideas that are similar to the ones they may replace will affect adoption positively by reducing the need for an individual to change. This highlights individual change as a limiting factor for change makers seeking to release more radical innovations that may not be as compatible with its potential adopters. One way of handling this is to release innovations in a sequence, where a compatible idea can help pave way for future innovations that are less compatible at the onset, in what amounts to a cluster of innovations.

Technology Clusters

Some innovations may be regarded as bundles of new ideas; where the adoption of one innovation may trigger the adoption of another more easily. Rogers (2003) calls these *technology clusters*, a bundle of distinguishable technological ideas that may be regarded as interrelated. Although the boundaries between individual innovations within a cluster remain in the eye of the beholder, a change agent may use this interrelationship in order to sell a specific package to a potential adopter instead of selling each innovation separately. In practical terms, this could involve the sale of hybrid seed technology, together with synthetic fertilizers and pesticides, tailored to work in unison, rather than selling each innovation individually – a successful approach in several Asian countries, where adopters preferred the innovation cluster – which in turn gave its users the added benefits of synergism between the individual innovations, increasing crop yields severalfold (Rogers 2003).

3 Materials and Methods

3.1 Interview Study: Experiences and Motivations

3.1.1 Choosing Respondents

This part of the thesis explores the experiences and motivations of some of the first farmers trialing/experimenting with Kernza. At this time, Kernza had only been introduced at two locations in Sweden: SITES Lönnstorp at SLU Alnarp (SLU, 2019), where it was a part of two long term field experiments, and a farm in Uppsala, Hånsta Östergärde (Solmacc, 2019) with ties to SLU Ultuna. Although an interesting development, these initiatives were too few to base a study on, which is why potential respondents were sought in the United States instead. These were mainly found through contacts with The Land Institute in early 2017, who in turn connected the author with a group of farmers; five out of which expressed interest in being a part of the study. Given the amount of time available, and the obstacles in finding more respondents in a country so far away from Sweden, the number of respondents had to be limited to five farmers. Luckily, the respondents already found represented a diverse group of individuals with different production systems, having experimented with Kernza for different durations of time. The farms ranged from 160 to 1200 ha in size, most of which were in the 160-200-ha range^{R3, R4, R5}. The respondents have trialed Kernza for a varied amount of time, some for as much as six years^{R5}, while others had just recently established their fields; having only seen a few harvests^{R1, R2, R4}, or still waiting for their first^{R3} at the time of writing. See details in the table below.

Respondent ID	Farm Description
R1	Conventional grain and cattle producer located in the great plains area. Trials/experiments with Kernza at a scale of 1.4 ha, planted in 2014. Learnt of Kernza through own scientific research.
R2	Organic grain and cattle producer located in the great plains area. Experiments with Kernza at a scale of 0.4 ha, planted in 2014. Learnt of Kernza through contacts at the Land Institute.
R3	Conventional grain producer located in the great plains area. Experiments with Kernza at a scale of 3 ha, planted in 2016. Learnt of Kernza through contacts at the Land Institute.
R4	Conventional producer focusing primarily on grass production and small grains, located on the west coast. Experiments with Kernza at a scale of 2 ha, planted in 2016. Learnt about Kernza through a friend.
R5	Organic grain producer located in the great plains area. Experiments with Kernza at a scale of 0.8 ha, planted in 2012. Learnt of Kernza through contacts at the Land Institute.

Table 1. Overview of respondents' backgrounds and farming contexts.

3.1.2 Qualitative Data Collection

Data collection took place between March and September of 2017 and included five semi-structured interviews by telephone in the spring, and in some cases, mail correspondence during the fall of the same year. The use of semi-structured interviews was an ideal approach in this case, as the interviewees were both short on time and moved around a lot, working the fields or conducting various farm activities (Bernard, 2006).

This involved creating an interview guide to make sure that the interviews were carried out in a similar way throughout the whole study; beginning with a presentation of the farm and its history, the introduction to Kernza, motivations, experiences, and problems solving, interactions with other growers and the future.

3.1.3 Thematic Qualitative Data Analysis

The interview data was transcribed from audio to text, coded and labelled under various themes, structured in accordance with the interview guide, with inspiration from the empirical data as patterns started to form during transcription. The process bore several similarities to both the inductive and theoretical thematic analysis described by Braun & Clarke (2006). According to Braun & Clarke (2006) inductive analysis could be seen as the process of data coding without use of a pre-existing coding structure, or pre-existing conceptions by the researcher; an approach where engagement with the literature may come at a later stage. In deductive or theoretical analysis, these steps are reversed; meaning that the researcher often begins the pursuit of knowledge with a theoretical framework in mind.

In this thesis, both approaches have been employed at a varying degree, beginning with the inductive method, which was used to categorize the data under various themes. For example, the respondents were asked “What made you interested in Kernza”, “How would you describe your experience of growing it so far?” and “How do you see the future of perennial crops on your farm” – which ultimately contributed to the themes: “motivations”, “general experiences”, “establishing Kernza”, “crop maintenance”, “harvesting Kernza” and “the future.”

Once the raw data had been categorized under these and other themes, a theoretical framework by Rogers (2003), focusing on the diffusion of innovations was applied to analyze the thematic data. At this point the method shifted from being inductive to become more theoretical. The theoretical framework by Rogers (2003) was used to explore how different variables affect innovation adoption; variables such as the relative advantage of the innovation, its complexity, observability, trialability and compatibility with the respondents’ values, experiences and previously adopted innovations.

3.1.4 Personal Integrity and Data Collection

All calls were recorded using the mobile application “TapeACall” available on Apples application store during the time of data collection. The respondents were made aware that the phone call would be recorded before the interview started, giving each respondent an opportunity to consent verbally. All respondents were made fully aware of how their responses would be used in the thesis at hand. Although contacts were established with help from the Land Institutes representatives, all possible care has been taken to keep all respondents anonymous. That said, certain information about the farms has been included in the thesis to give the reader a better context when reading the results and discussion sections.

3.2 Microbial Biomass Estimation

3.2.1 Site Description

The site used for the microbial biomass estimation and comparison was located at SITES Lönnstorp research station in Alnarp (55.67°N, 13.10°E) southern Sweden (Field Sites, 2018). This area is commonly characterized by a humid and continental climate (Peel *et al.* 2007), hosting loamy soils with approximately 15% clay and 3% organic material (SLU, 2018a), and pH-levels ranging from 6.8 at 0-20 cm depth, 7.4 at 20-40 cm depth and 8.1 at 60-90 cm depth (Dimitrova Mårtensson, pers. comm). The site received an accumulated precipitation of 670 mm in 2016, while the mean annual temperature was 9.4°C in the same year. In 2017, the site received an accumulated precipitation of 650 mm, while the mean annual temperature was 9°C (SLU, 2018b).

3.2.2 Experimental Design

Two pre-existing long-term field trials were used in this study: SITES Agroecological Field Experiment (SAFE), and a three-year old Kernza experimental field. SAFE harbors four different cropping systems, two of which were used in this paper. These include agroecosystems cultivated with (i) annual winter wheat in a conventional crop rotation and (ii) the perennial cereal Kernza, grown in two treatments; as a sole-crop and in a biculture with the perennial legume lucerne. These three treatments were compared with the three-year old Kernza experiment located near SAFE. The plots in SAFE were replicated in four different blocks, while the three-year Kernza experiment consisted of a pseudo replication, e.g. one field divided into four smaller plots.

Before SAFE was established, the whole area went through a preparation cycle, where barley was grown as a pre-crop for a full year. Prior to that, the same fields were used in another long-term field experiment, established in 1974 meant to compare different tillage intensities (Larsbo *et al.* 2009). Meanwhile, the three-year old Kernza crop was sown on land previously used for rapeseed production in a conventional crop rotation (Rasmusson, pers. comm).

The SAFE plots used for Kernza and the Kernza-lucerne biculture were sown 2-3/5, 2016, whereas winter wheat was sown 14/9, 2016 after one season of spring oilseed rape – the first crop in the conventional crop rotation. During the establishment year, the Kernza plots were resown a few times to increase stand density, and to homogenize replicate fields. The three-year old Kernza was sown in September 2014.

The three-year old Kernza field received 150 kg N27, corresponding to 40 kg N ha⁻¹ yr⁻¹, synthetic fertilizer 6/4, 2016, whereas the SAFE agroecosystems did not receive fertilizers this year. In 2017, the three-year old Kernza received 150 kg NPK 27-3-5 ha⁻¹ yr⁻¹ synthetic fertilizer on 18/4, while both one-year Kernza treatments (sole- and intercropped) received 444 kg Biofer 9-3-4 organic NPK ha⁻¹ yr⁻¹ on 4/5, a few weeks later. Meanwhile, the winter wheat treatment was fertilized twice during 2017: 210 kg NPK 27-3-5 on 17/3 and 370 kg NPK 27-3-5 on 18/4, totaling 580 kg ha⁻¹ yr⁻¹ of synthetic fertilizer (Rasmusson, pers. comm).

During these two years, the conventional winter wheat system was sprayed with pesticides on five occasions. First with herbicide in the spring oilseed rape pre-crop (1 L ha⁻¹

Fox and 165 g ha⁻¹ Matrigon) on 13/5, 2016, followed by the insecticide Mavrik at 0.3 L ha⁻¹ on 3/6. A new round of herbicides, including Boxer and Diflanil were applied at rates 1.5 L and 0.1 L ha⁻¹ respectively on 18/10 after winter wheat had been sown. In 2017, fungicides were applied twice, once on 18/5 including 0.2 L Acanto and 0.4 L Proline ha⁻¹ and a second time on 15/6 when Amure was applied with a concentration of 0.4 L ha⁻¹; both applied after soil sampling took place (Rasmusson, pers. comm). The two perennial treatments within SAFE were organically managed, and thus did not receive any pesticides, but the three-year old Kernza treatment was sprayed with herbicide Starane XL at 2.5L ha⁻¹ on 27/4 2015, during its first spring season.

3.2.3 Soil Sampling

Soil cores were collected on the 27/4, 2017 following a stratified design. All samples in SAFE were collected along two lines in the 24-48 m wide fields, beginning and ending circa 10 m from the edge of the fields, with approximately 30 m between sample points, see Figure 1 below. Sampling from the three-year Kernza experiment followed a similar design, although these plots were considerably smaller, totaling only 14 m in length and 8 in width. In this case, collection points were chosen in every corner of the rectangular fields, 2 m from both of the closest two edges. Samples were collected using a Wintex MCL3 soil corer, capable of extracting 2 cm diameter cores down to one meter.

Soil cores were collected at four different depths: 0-5 cm, 5-30 cm, 30-60 cm, 60-90 cm in four locations per field, after which the same-depth samples were mixed together, and then freeze dried and stored at -20 °C awaiting extraction. In the event that a soil sample could not be retrieved, such as when the soil contained too much rock prohibiting drilling, a new sample was collected close to the original collection point. This procedure was also used when parts of the soil core was empty or full of small rocks. Together, the 4 mixed samples representing the four depths of each treatment × the 4 treatments × 4 replicates amounted to a total of 64 samples (see Table 2 below).

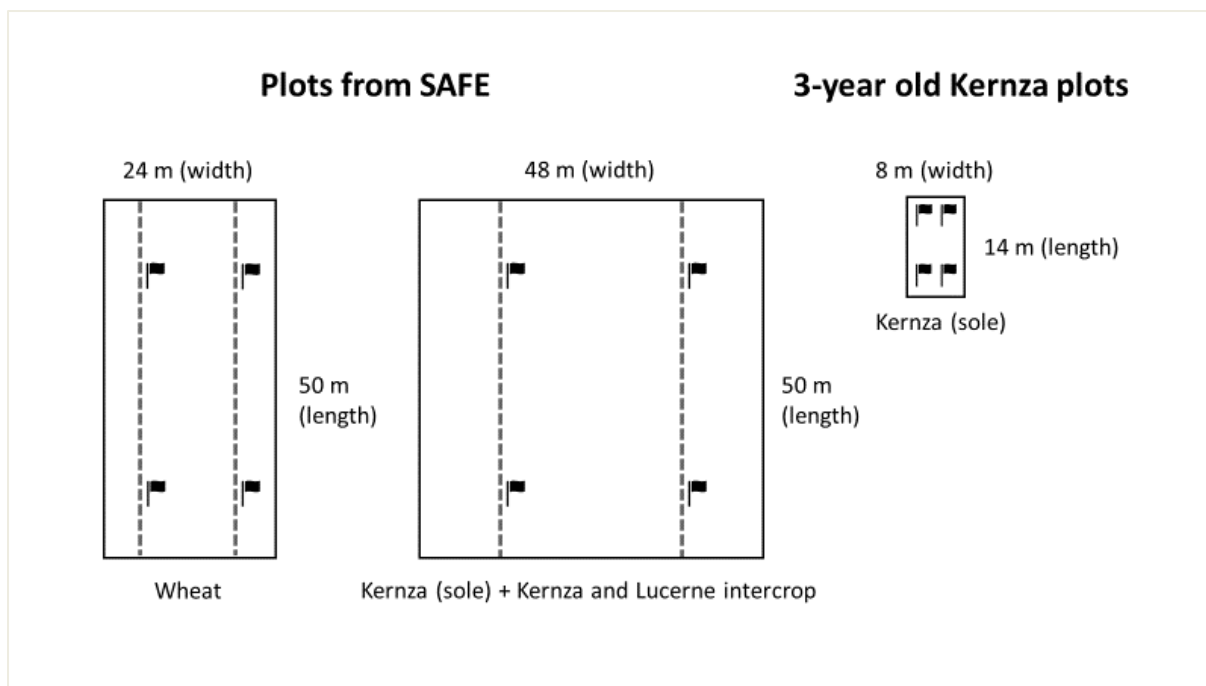


Figure 1. Visualization of various field sizes and sample points. Each flag represents a core sample location, each giving rise to four subsamples from different depths (0-5, 5-30, 30-60 and 60-90 cm).

TREATMENT	DEPTH	SAMPLES	REPLICATE(S)
WINTER WHEAT	0-5 cm	4 subsamples mixed into 1 (see Fig. 1)	* 4
	5-30 cm	-"-	* -"-
	30-60 cm	-"-	* -"-
	60-90 cm	-"-	* -"-
1-YR SC KERNZA	0-5 cm	4 subsamples mixed into 1 (see Fig. 1)	* 4
	5-30 cm	-"-	* -"-
	30-60 cm	-"-	* -"-
	60-90 cm	-"-	* -"-
1-YR IC KERNZA	0-5 cm	4 subsamples mixed into 1 (see Fig. 1)	* 4
	5-30 cm	-"-	* -"-
	30-60 cm	-"-	* -"-
	60-90 cm	-"-	* -"-
3-YR SC KERNZA	0-5 cm	4 subsamples mixed into 1 (see Fig. 1)	* 4
	5-30 cm	-"-	* -"-
	30-60 cm	-"-	* -"-
	60-90 cm	-"-	* -"-
Total samples			= 64

Table2. Total number of samples, where SC stands for sole crop and IC for intercrop.

3.2.4 Laboratory Analyses

The process of analyzing the fatty acid profiles in the soil samples was divided into four steps: soil extraction, lipid fractionation, mild alkaline methanolysis and gas chromatography (GC). In the first step, 2 g of freeze-dried soil was put in a 50 ml test tube before adding 15 ml of citrate buffer, methanol and chloroform (0.8:2:1 v/v/v) to the tube, a procedure adapted from (Bligh & Dyer 1959) and later used by (Frostegård & Bååth 1996) in soil research. Next, the sample was vortexed for one minute, and then extracted for two hours at ambient room temperature before being centrifuged at 5000 rpm for 10 minutes. The supernatant was then transferred into a large glass tube, while the remaining soil was washed with 5 ml of the same citrate buffer, methanol and chloroform mixture used before. The remaining soil was then vortexed and centrifuged again, after which the new supernatant was added to the one above. In the next step the phases were split by adding 4 ml chloroform (CHCl_3) using a pump, and 4 ml citrate buffer using a plastic pipette tip, before being vortexed for two minutes and left at ambient room temperature overnight. On the next day 3ml of the lipid extract was transferred from the lower phase to be evaporated over a 40 °C heating block under a stream of nitrogen.

In the second step, lipids were fractionated into different classes, including neutral lipids, glycolipids and phospholipids. Pre-packaged silica columns were placed in a test tube rack above a set of glass test tubes. The dry extract from step one was then dissolved in 100 μl CHCl_3 , after which the solution was vortexed for 15 seconds. The neutral lipids were then extracted from the solution using a 1.5 ml CHCl_3 solvent. This process was repeated for phospholipids, using 1.5 ml of methanol (MeOH) to eluate the sample, after which all test tubes were once again steamed with nitrogen on a 40°C heating block.

The third step of the process involved separating the fatty acids from their lipid backbones to combine these with methyl esters that could be analysed in a gas chromatograph. This process began by adding 100 μl of the internal standard fatty acid methyl esters (FAME) 19:0 to the samples, which acted as an internal standard. In the next step, the vials are evaporated under non-heated nitrogen steam. The samples were then dissolved in 1 ml of toluene:methanol (1:1) and vortexed for 5 seconds. In the next step 1 ml 0.2 M potassium hydroxide (KOH) dissolved in methanol was added to the samples, which were then incubated in a water bath for 15 minutes at 37°C, before cooling for approximately 20 minutes. In the following step, 2 ml of hexane:chloroform (4:1), 0.3 ml of acetic acid and 2 ml of H_2O was added to the samples, which were vortexed for one minute. After checking the pH of the lower solution (aiming for 6), the samples were centrifuged for 5 minutes at 3000 rpm in order to transfer the upper phase of the solution before evaporating the final sample under steaming nitrogen, without adding any heat.

In the fourth and final step of the analysis a GC – 17 A Gas Chromatograph SHIMADZU) with a column CP – Wax 58 (FFAP) CB was used to identify and quantify the different fatty acids contained in the final samples. In this step the neutral and phospholipid fatty acids were diluted in 200 and 150 μl of hexane, respectively, before transferring 100 μl of each solution into smaller GC vials to be used in the Gas Chromatograph.

3.2.5 Statistical Analysis

A One-way Analysis of Variance was used to detect differences in PLFA 16:1 ω 5 between the agroecosystems, while a T-test was used to detect differences in PLFA 16:1 ω 5 between the depths, as a result of missing data or values under the detection limit in the two deepest soil layers. But a One-way ANOVA was also used to detect differences between agroecosystems

and depths in NLFA 16:1ω5, individually. Both ANOVAS were accompanied by Tukey's Post Hoc test with a significance level of $p < 0.05$ to separate the means. All statistical analyses were made using IBM SPSS 24.

4 Methodology & Theories Discussion

4.1 Criticisms of Adoption/Diffusion Research and Interview Methods

Research into the realm of innovation diffusion began in the 1940's with the first formulation of the diffusion paradigm. In the following two decades, the field grew tremendously, both in the United States, but also in other countries, especially developing ones. But during this period, the field severely lacked introspective criticism. Little research highlighted potential biases or problems with theories and methods, a gap in understanding which persisted until the 1970's. Since then, the field has started to acknowledge these problems.

According to Rogers (2003) these include for example the *pro-innovation bias*, the *individual-blame bias*, the *recall problem*, and the *problem of equality*. Diffusion research relies upon simplified models of reality to draw conclusions about individuals' behaviors, generalizations that are true to a certain degree. But the above stated shortcomings of diffusion research are important to keep in mind, as in all research.

The Pro-Innovation Bias

The Pro-Innovation Bias is one of the most problematic shortcomings of diffusion research, commonly expressed as the assumption that all innovations must be diffused among all members of a social system, that diffusion should happen rapidly, and that re-invention and rejection is wrong (Rogers 2003). These biases have stalled research into fields such as re-invention, the underlying causes behind rejection, or anti-diffusion programs that emphasize blocking innovations that may be harmful to people and society. Over time, these biases have resulted in us knowing more about rapidly spreading innovations than those that diffuse slowly, more about how adoption takes place – and less about how and why rejection happens, and how continued use looks like compared with discontinuance; which essentially amounts to us knowing more about success than failure.

In order to overcome the Pro-Innovation Bias, Rogers (2003) argues the following:

- That research into diffusion need not happen after the case, but could be initiated before an innovation is released or during the diffusion process.
- That researchers and scholars must be more aware of how they select innovations, taking into account whether they select a successful or unsuccessful innovation, or even choosing to compare two similar innovations, where one was successful and the other was not.
- That researchers must acknowledge that rejection, discontinuance and re-invention is a natural part of the innovation diffusion process, and that individuals exhibiting such behaviours may do so because it makes sense for them, and is rational for reasons not comprehended by researchers without further and detailed inquiry.
- That re-invention is an important tool for individuals seeking to adapt a potential solution to his, hers or a group's particular problems.
- That the broader context is important – such as policy decisions and previous innovations and practices already in use.

- That researchers focus more on the motivations behind adoption and rejection, even though this necessitates interviewing methods that also harbor a certain degree of problems.
- That researchers should question the assumption that economics drive adoption, opening the door to other, hidden motivations.

The Individual-Blame Bias

The individual blame bias is the tendency among researchers to assign individual blame to someone for their problems, rather than the system in which they are embedded (Rogers 2003). In innovation and diffusion research, this can be seen when individuals that are categorized as late adopters or laggards are blamed for rejecting an innovation, or choosing to adopt it too late; groups of people who may be described as irrational or resistant to change, when in fact, the innovation may not be appropriate for the group in question. A remedy to this may be to instead focus on the system, questioning whether the innovations were actually in tune with the needs of the individuals. If not, Rogers (2003) notes that this kind of behavior may become a self-fulfilling prophecy, where late adopters may be ignored, which in turn makes the group less likely to adopt the innovation in lack of information and support.

The Recall Problem & Causality

Another important hurdle in the process of studying diffusion is understanding and taking into account how time affects the respondents in a study and their ability to recall past events (Rogers 2003). In the past, most research took place at one point in time, asking respondents to recall the adoption process in detail. But as Rogers (2003) notes, hindsight is not entirely accurate, as individuals are affected by their relationship with an innovation, their personal qualities and circumstance such as memory and education, and the length of the period being studied. Considering how important a variable time is in diffusion research, guarding against recall errors is essential; something Rogers argues could be done by use of research designs such as field experiments, longitudinal panel studies, use of archival records, or through case studies using all of the above in combination. But time is also an important aspect of causality, such as when determining the time order of events, or what variables affect each other. What causes innovation and innovativeness? Answers to these questions hinge on the time order being correct, and in researchers employing the correct research designs that take into account causality.

The Problem of Equality

But the socio-economic benefits of innovations are not always equally distributed among members of a social system. In some instances, they instead widen the gap between high-status and low-status individuals, which leads to inequality. In developing countries with different social structures, this may hinder individuals with a low socio-economic status from accessing technological innovations, whereas high-status individuals with more wealth and education will receive adequate help from development- or change agencies. An example of this, is when a progressive farmer with a higher socio-economic standing wants to adopt a new idea; a farmer whose relative size may make him or her easier to target from a change agents' perspective. This farmer is more likely to receive help than a smaller farmer who, in the eyes of the change agent might be less likely to adopt the idea – which in turn widens the

gap between the two over time. To combat this, strategies that target low-status individuals with innovations more suitable to their needs and situation must be employed.

4.2 Different Methods to Determine Microbial Biomass

Several methods exist to study the microbial biomass and community structure of soils. These can be divided into culture-dependent and culture-independent methods, all exhibiting different advantages and disadvantages (Hill *et al.* 2000). One of the more commonly used culture-dependent methods consist of *dilution plating*, where microorganisms are grown on culture media and counted as colony-forming units (CFUs). This method can be used to study several different microbes – but it is limited by the growth media and environment used to culture these organisms, which only accommodates 0.1-0.5 % of all microorganisms present in soils (Torsvik *et al.* 1990). *Community level physiological profiles* (CLPP) is another widely used method, making use of the fact that different species of microorganisms utilize different carbon sources, which can be used to create profiles for different microorganisms (Hill *et al.* 2000). If microorganisms utilize the same resources, they are deemed functionally similar, while if not, they are deemed functionally dissimilar. But this method suffers from the same bias as the dilution plating method, unless the substrate or growing environment used is more ecologically similar to substrates that could be found in natural settings. These limitations underscore why culture-dependent techniques are not optimal for studying the composition of natural microbial communities as a sole method, which ultimately disqualifies their use in the study at hand.

Alternate methods are more culture-independent, such as using nucleic acids or fatty acid estimation techniques to characterize the soil community being studied. *Nucleic acids* can be analyzed using three categorically different methods; in situ analysis, direct analysis of extracted DNA/RNA or the use of polymerase chain reaction (PCR) techniques (Paul 2014). These techniques have many specific advantages and disadvantages, most of which will not be addressed here. But when aiming to characterize functional groups in a specific soil, the PCR-technique stands out in its capability to amplify specific genes that code for functions of interest. For example, this method makes it possible to study the presence of genes responsible for BNF or denitrification in a soil sample, something not possible with the techniques mentioned before. But PCR-methods are susceptible to bias on several levels too. Samples are often very small, commonly weighing in at only 500 mg of soil – which may create a non-representative picture of the soil community. Preferential amplification is another cause for concern, as in some cases, polymerase will bind more easily to some sequences over others. A completely different problem is the fact that some organisms contain several copies of specific sequences, which can create a situation where these sequences are overrepresented in the results. Still, these techniques have proven invaluable to researchers over the past 20 years and represent one of the best tools for studying microbial communities. But in place of nucleic acids, this thesis will instead use *phospholipid fatty acid* (PLFA) and *neutral lipid fatty acid estimation* (NLFA) techniques to study the communities at hand. These two techniques also are culture-independent, but rather than measuring the amount of RNA/DNA sequences in a sample, they instead measure the presence and relative quantities of fatty acids. PLFAs can be found in the phospholipid by-layer in the cell membranes of microorganisms, while NLFAs are contained in arbuscular mycorrhizal fungi (AMF) storage structures such as vesicles and spores (Olsson *et al.* 1995). Some of these fatty acids are unique for different microorganisms, and as such, can be used as signatures for identification (Tunlid

& White, 1992). This signifies an opportunity to learn more about how the microbial community in different soils are structured, but it also poses several limitations – as this method can only be used to identify microbial functional groups, not specific species. Some of these organism groups, such as AMF can be detected using this method (Olsson *et al.* 1995), but when attempting to identify free-living or symbiotic nitrogen-fixing bacteria these techniques are not adequate. These organisms belong to larger groups of microorganisms who may share the same fatty acids, making it impossible to distinguish between nitrogen fixing organisms and non-fixating organisms.

5 Results Part I: Producing and Launching a Perennial Grain

5.1 Interview Study: Experiences and Motivations

This part of the thesis revolves around the experiences and motivations of five American farmers in text defined as *Respondents* “R” 1-5) who have experimented with or is currently experimenting with Kernza. Information about the respondents and their coding can be found in the materials and methods section. In this section, and throughout the paper, experimenting is generally synonymous with trialing – which is to say, testing the crop in a practical setting.

5.1.1 General Experiences

The experience of growing a new crop like Kernza varies a lot with location, type of production system, years of experimentation and access to adequate machinery, among many other things. But there are also similarities between the different farmers’ experiences – mostly relating to establishment issues and the current lack of know-how. Among the five respondents, one had not yet harvested their first seeds^{R3}, one chose to harvest only the hay for feed^{R2}, two focused on harvesting only the seeds^{R4, R5}, while the last one harvested both the hay and the seeds^{R1}.

5.1.2 Crop Establishment

The group had varying opinions about the complexity of establishing Kernza. Two farmers found the process very problematic, citing issues with both machinery, seed size, climate, and timing^{R1, R3}, while the others, although sympathetic to the issues of the farmers above, only mentioned these in passing. With regard to timing, all farmers in the study decided to plant their Kernza in the fall – giving the crop almost a full year to develop before its first harvest in the second year. A few of these farmers got their seeds a bit too late in the fall^{R3, R4}, but still chose to sow the crop as quickly as possible, which in some cases effected establishment negatively.

When asked about how their current machine parks worked in the establishment phase, the interviewed farmers had varying answers. For example, one farmer stated that Kernza cannot be established properly with regular seeding equipment – arguing that most planters and drills are not suitable because the seeds are just too small^{R1}. To get Kernza well established on their farm, they therefore opted to use a Brazilian grass seeder. The notion that the seeds are very small is shared by a second farmer, who in contrast argues that ordinary

grain drills do work; albeit with a lot of metering to get the seed planted at a shallow depth^{R3}. Their success is shared by a third farmer who drilled in September using a modern grain drill and a culti-packer to pack it in^{R2}. They state that this would work with other drills in their machine park as well, such as their no till drill, and their Brillion seeder. Respondent 5 puts it this way:

“...Establishment I think shouldn’t be too difficult if we have a firm seed bed, but I know when I planted in 2011 I literally planted it in the dust, but over the winter and in the spring, it started coming on, and it came on very good. I think the challenge is to get a firm seed bed and that might be something producers are not really accustomed to.”

The last farmer^{R4} in the group used a 1980’s 3.7-meter-wide grain drill for seeding, with its coulters set at a 46-centimeter spacing and 8 coulters under the drill. As a result of seed shortage, their seeding density was only about 4 kg ha⁻¹ – but ideally, they would have wanted it to be closer to 9 kg ha⁻¹.

5.1.3 Crop Maintenance

Several farmers agree that knowledge of how Kernza should be maintained is still under development, characterized by a lot of experimentation, consultation with partner organizations and research, and not oriented towards high production, but rather towards creating a stable stand that maintains its yields. But when asked about how they think Kernza should be maintained over the years, several farmers see clear parallels to how farmers currently maintain other perennial plants. One farmer^{R1} goes as far as to state that the knowledge of how to grow Kernza is already out there – among growers of lucerne and brome grass; forage crops with similar rotation times which may act as inspiration for new Kernza growers. But solutions to problems unique to Kernza are still being investigated, and the newest information about this is best found among the action-oriented researchers at TLI, its partner universities, and the farmers they collaborate with.

5.1.4 Harvesting Kernza

Only three out of the five respondents had harvested any Kernza seed by the time this interview took place^{R1, R4, R5}; out of the other two, one was currently only harvesting the straw for forage^{R2} a result of the small plot size, low seed yield, and weed problems, while the final one was waiting on next year’s harvest^{R3}.

One of the farmers who had harvested the grain described the process as a bit problematic, stating that the combine tended to scoop up a lot of plant residues that was not cleaned out as it would have been had the farmer grown a more common plant like wheat^{R1}. But when inquired once more about the farm’s machinery the same farmer noted no problems at all. Their machine of choice consisted of a modern combine harvester intended for cereal grain crops.

A second farmer, who has had three years of harvesting experience with Kernza is sympathetic to these issues but explains in more detail how the harvest is done in practice – and why they think ordinary machinery will do just fine for Kernza^{R5}. In their operation, they

use a windrower to cut the grain before putting it in a swathe. In the next step they use the same combine as they use for their other crops, with slight adjustments to its settings.

“It’s dehulling and cleaning where the challenge is.” – Respondent 5

The idea to swathe the Kernza instead of direct combining it is shared by both of the above farmers^{R1, R5} as the most common way to harvest Kernza; but the final grass-seed farmer^{R4} did try to direct combine the Kernza in 2017 – a tactic intended to avoid capturing too many weed seeds. This method would have simplified the harvest considerably, but the problem was that both the straw and the seeds still contained too much moisture after harvest, and with the lack of a seed drying machine, the farmer in question had to spread out and dry the seeds manually in a barn, instead of just drying it in the field after swathing.

“I did not swathe the field. I cut it standing using a 7720 John Deere combine with a 4.6m [Converted from ft] wheat header. Unfortunately, by not swathing, the seed moisture was way too high – around 16%. So, I had to spread the seed out on my shed floor for drying for 2 weeks.” – Respondent 4

But even if the farm had owned a seed drying machine, Respondent 4 remains unsure if direct combining would have been possible because of the moist straw potentially clogging up the machinery. For them, the next harvest will therefore have to be swathed, where the cut plants will be dried in the field for 6 days, before being combined by a belt pickup header.

5.1.5 Crop Rotation and Animal Integration

Most of the respondents^{R2, R3, R4} agreed that integrating Kernza into their daily operations is a complicated process, highly dependent upon the circumstances at each farm; if the farm is primarily focused on grains or animals, and their knowledge and experiences of growing other perennials. One farmer^{R2} outlined in detail how complicated this would be, stressing that there are still too many unknowns to get it to work. A feeling mirrored by respondent 3 who was uncertain of Kernza’s place within an annual rotation; underscoring that the crop is still very young and that new users should not have too high expectations on the crop just yet. Meanwhile, another farmer^{R5} argued the opposite, stating that Kernza could potentially be managed in the same way lucerne is today:

“Like I was telling a person interviewing me yesterday: it [Kernza] has the potential in that is very similar to the lucerne crop I currently grow on my farm. We establish it in the first year and then in the 2nd, 3rd and 4th year we harvest it, and at the end of the 4th year we terminate it.”

A notion mirrored by respondent 1, who states that finding the best available agronomic practices is important – an endeavor which should not be too hard, considering the fact that most forage plants are perennial, such as brome grass and lucerne; crops growers are familiar with getting established and having in production for up to 6 years. But in contrast with lucerne, Kernza still has a few issues that need to be sorted out, including sotting, the tendency of the crop to “thicken” up after 2-3 years of production, which consequently reduces productivity significantly. However, as long as this is taken into account, both respondents 4

and 5 see no problems finding ways to include the crop into a rotation. Taken together, these problems represent a few of the current shortcomings of the crop. But there are several other advantages with it as well, like for instance using both the seeds and forage for human and animal consumption: an advantage highlighted by both respondents 1 and 2, who both used the Kernza hay to feed their cattle. According to respondent 1, this is one of the strongest advantages of Kernza – using it as a dual-use crop to produce both food and high-quality feed.

“In the future, Kernza might grow best by marketing it as a dual-use crop in combination with subsidies to get it started on marginal or high-risk land [...] possibly leading to the adoption of more acreage in the future.” – Respondent 1

But there are other advantages as well, including using the crop where it makes the most impact, both environmentally, and economically:

“[...] put it [Kernza] on soils that need permanent vegetation like rolling hills with a lot of slopes prone to erosion, hills that probably couldn’t be farmed with row crops. [...] fields that could be pasture or permanent vegetation that aren’t very valuable soils and you’re able to get a reasonable yield. [...] That would help. But if you put Kernza on a field like I have it now, which could also grow other crops and do it sustainably then you haven’t gained much necessarily.” – Respondent 3

5.1.6 Knowledge Platforms and Information Sharing

Kernza is a relatively new crop on the market, still being explored by researchers and farmers trying to determine how to grow it, as well as creating and maintaining channels to make this information more widely available. At present, these channels primarily consist of The Land Institute and its partner universities, as well as Plovgh, a sourcing partner in specialty grains and crops, who in this case act as a middle hand in distributing the crops and selling the harvests, as well as offering advice along with TLI and the universities. When in need of advice, some farmers may contact TLI directly^{R1, R4}, some contact Plovgh^{R3}, whereas some have specific contacts at universities they collaborate with^{R5}. But others choose to go beyond these institutions, as in the case of respondent 2, who contacted the network organization “Green Lands, Blue Waters”, GLBW, whenever they needed help. Given that Kernza is still under development, best practices can shift fast, and advice that was accurate yesterday, may become outdated quickly:

“We just have to acknowledge that this is the case with a new crop. They’re doing the best they can with the crop’s brief history, few farmers, it is early on, but as we go along, we will have our answers. Even when I’ve talked to them within the span of a year, I’ve gotten new answers and things have changed. So that’s the dynamic that we just have to accept right now.”

– Respondent 3

This dynamic makes extension complicated, and although no digital platforms for knowledge dispersal exists [at the time of writing] there are organized meetings and conferences that attempt to do this more in depth. These include conference calls held by Plovgh, who help gather farmers, universities and researchers from all over the US to discuss some of the issues people are experiencing. Other forms of information sharing activities include on-farm visits,

both by existing, and potential growers, neighbors, or scientists conducting research, like those involved in the Forever Green Project at the University of Minnesota:

“[The Forever Green Initiative] that’s probably the project that I really stay connected with. Because Kernza is a part of that project, where we look at some other perennials, as well as crops like pennycress that we’re trying to relay crop with or double crop with. But Kernza is part of that whole project. So, keeping connected with the evergreen [initiative] is how I’ve stayed connected with the Kernza thing.” – Respondent 5

Together, these serve as the main conduits through which information is shared among growers and the institutions mentioned above. Few of the respondents in this study had access to other informal networks, but rarely shared experiences with other Kernza growers, relying completely upon their respective contacts at the organizations described above.

5.1.7 Motivations

The underlying motivations for experimenting with Kernza varied a lot within the group, ranging from using it as a weed control strategy^{R2}, volunteering farmland for research purposes^{R1, R2}, seeing possible profits in seed stock production^{R3, R4}, to desires of introducing more sustainable production practices both on farm and in society^{R3, R4, R5}. But the most common response was to simply plant it to see how well it would grow, with little to no expectations at all.

For the grower^{R2} who used it as a means of controlling weeds, Kernza, together with winter rye – a fall seeded annual, presented the farmer with a possible tool to combat a very tenacious weed in their organic production system: the giant ragweed, *Ambrosia trifida*. This plant was causing havoc in said farmers production system, and in search of more radical ideas to deal with it, Kernza and various fall seeded annuals appeared to present a solution to the problem. For respondent 1, who also happened to work with Kernza as a researcher, the interest in growing and experimenting with the plant had more to do with its breeding potential than anything else. They were curious about how it could be modified using new breeding technologies, and how genes from Kernza could be moved into some of its relatives, such as wheat. At two of the three remaining farms, experimentation, the promise of ecosystem benefits and the possibility of profiting from growing Kernza seed stock is highlighted as important motivations. This group consisted of two grain producers^{R3, R5} and a grass-seed producer^{R4}, the latter of which wanted to move more into the millable seed market, breaking production cycles with grass seed production that necessitates a lot of chemicals – a grass that necessitates less pesticides to maintain, compared with grass seeds grown for lawns, where purity is a much higher priority.

“I want to grow edible, millable seeds. We grow too much grass seeds in this valley – and we need something to rotate with. Also, the world needs food. The world doesn’t necessarily need lawns that you need to cut and water. I see the future coming, and I just want to be in the early stage of that. I think it’s going to have to change.” – Respondent 4

For another respondent, maintaining and improving soil health stands out as the most important motivation behind experimenting with a crop like Kernza. They explain that it makes

no sense to only have a living crop growing in the fields four months per year – and that we need to move in a new direction:

“I’ve always been someone interested in thinking outside the box, but part of the reason I’m so interested in Kernza specifically and perennials in general is the need for us to more diligently take care of the soil here” – Respondent 5

They go on to describe the drawbacks of corn and soy, two crops that are great at generating revenue, but challenging in terms of maintaining soil health; the polar opposite of a crop like Kernza, which they believe holds unlimited potential in terms of restoring soil, wildlife and pollinators in agricultural production – attributes that fit the mold when we sculpt our future agroecosystems.

These attributes appeal to several of the farmers, including respondent 3 who sees the long-term potential, should the mission to develop and grow these crops as envisioned succeed; but whose interest is more grounded in the near-term future, where the crop might serve an important purpose reducing erosion in for example rolling landscapes.

5.1.8 Experimentation and Innovation Adoption

A part from experimenting with Kernza, several of the respondents had also adopted other Agroecological innovations, spanning from conventional no-till practices with herbicide resistant crops, as in the case of respondent 1, to narrow strip-intercropping^{R2}, intersowing pasture and clover-seeds in a growing crop^{R2, R4}, and various forms of organic no-till^{R5}.

“We did narrow strip intercropping for 6 years where corn, soybeans and oats were grown in 3.7m [Converted from ft] wide strips repeated across the field.” – Respondent 2

“Lots of no-till going on here [...] and we do some companion-cropping here, where we intersow red clover underneath for example oats, you harvest the oat and the clover grows for the next year. Great to only work ground and plant one time. Clover is bigger next year as it has one plus year of growth. I’m big into intercropping. In fact, I see the potential in intercropping with Kernza!” – Respondent 4

Other examples include the adoption of new crops and seed varieties^{R2} that fit the needs of each individual farm.

While some of the farmers have experimented with a few new practices, others have chosen to implement several at the same time. Respondent 5 highlights several experiments over the past 15 years, including reduced tilling during the fall, experiments with undersowing red clover in small grains, reduced deep tillage (18-23 cm) to once every 3 years, inclusion of perennial crops like lucerne with deep tillage only every 6-7 years, complex rotations with a diversity of crops and experiments with hazelnut production.

“[...] And so, moving that whole concept around 162 ha [Converted from acres] goes a long way in building soil structure, microbiome area and all the other ecosystem services that go along with it.” – Respondent 5

5.1.9 The Future

When inquired about the future, several of the farmers expressed keen interest in continuing their experimentation with Kernza, while others were hesitant, wanting more time to analyze how well the crop performed before making new plans:

“I think there’s a lot of potential, even more a few years down the road when the breeding process has led to bigger seeds, I think if the yields can come up to around 50-60% of wheat then it becomes a much more viable option. [...] I think that I’d give it another year to see how the crop performs. And then I think that it kind of depends on having it as a forage crop, and depending upon if there’s a continued high demand for the seed.” – Respondent 1

Respondent 2, in contrast, had no plans to continue with the crop, but stressed that they were very sympathetic to the crop and its potential, hinting at future opportunities should the crop fit into the current farming operations at such a time. Meanwhile, others go beyond their desire to keep up with Kernza by also expressing interest to try other perennial crops:

“Possibly interested in new crops from The Land Institute, know they’re working with for instance perennial sorghum. This area hasn’t traditionally been used to produce sorghum, so some of those crops would have to fit in, and they’d fit in some environments better, and there’s been a market for some of the other grains in other states.” – Respondent 3

One of the respondents^{R5} had worked closely with researchers for many years, and thus, possessed a lot more knowledge and potential interest in experimenting with other perennials compared to the rest of the group; declaring immediate interest in experimenting more with both perennial pennycress, flax and sunflower.

“[...] If we can ever get perennial flax developed, there’s no question that I would love to work with it as well. So those would be the ones that I’d jump at immediately. The other ones they’re working on is the perennial sunflower, and if that gets to be where its commercially viable, I’d be totally interested in working with that as well.” – Respondent 5

A sentiment mirrored by respondent 4, who, after learning about other perennial initiatives states:

“Perfect! I want to stay very close to the Land Institute and if they continue to use Plovgh, I want to stay very close to those guys. Because I think they’re on the vanguard of what agriculture has to turn into. [...] I’d love to introduce more of these perennial plants here, in fact I didn’t know that [...] The Land Institute had that in their plans or were working on that. [...] I’m totally into that. Absolutely. I’d love to include intercropping too.” – Respondent 4

5.2 Analysis: Variables Affecting Adoption

In this chapter the empirical data collected in the interview study was used to perform an innovation diffusion analysis focusing on the variables that appear to affect adoption of an innovation – in this case Kernza. Is the innovation compatible with the values, experiences, or previously adopted innovations of the respondents? What relative advantages do the respondents highlight as important? Are they finding the innovation too complex? How easy is it to trial, and what opportunities exist to observe its performance?

Relative Advantage

The relative advantage of an idea is one of the strongest predictors of how fast it will spread within a system. The respondents in the study highlight several advantages that motivated them to experiment with Kernza, including growing a crop that contributes to soil health^{R5}, allowing the farmer to move beyond minimum-tilling practices and opening the door to other ecosystem services as well. The other respondents underscore the benefit of the crop to produce both food and feed^{R1}, its competitiveness against weeds^{R2}, and in the case of the grass seed farmer^{R4}, the opportunity to grow food for human consumption with crops exhibiting the same growth habits [being perennial] as the rest of their crops; a crop that fits within the existing machine park and production system.

Complexity

Incorporating Kernza into the daily operations of a farm presents several challenges, highlighted by the respondents of the study. These include problems during the establishment phase^{R3}, knowing how to maintain the crop once it is planted^{R1}, before finally harvesting it. But integrating the crop into a crop rotation is also ridden with complexity^{R2}. This ties back to the fact that Kernza is still under development – and that advice is continuously shifting^{R3}, and only available through TLI, its' partners and Plovgh, with extension services still being in the dark^{R5}. Despite this, all respondents found ways to tackle this complexity, finding solutions that fit on their farms, though some argue it to be more complex^{R3} than others.

Trialability

Trialability is an essential aspect affecting the adoption of new ideas, giving the potential adopter a chance to test the innovation in their highly individual setting, which in turn may reduce uncertainty, should they continue through the adoption process and actually adopt the idea (Rogers 2003). For the respondents in this group, some individuals have chosen to trial the crop together with researchers^{R3, R5}, as researchers^{R1} while the rest primarily experimented with it on their own^{R2, R4}.

Observability

Out of all five respondents, two explicitly say that they accept farm visits where they talk about Kernza, in one case through interviews^{R5}, and in another, accepting growers and researchers to visit and see, or take measurements of the crops^{R3}. This increases the observability of how the crops work, both by seeing it in person, but also through the communication of information, which in turn influences the adoption rate (Rogers 2003). It remains unclear how many of the respondents had personally observed Kernza prior to them deciding to trial it.

Compatibility

Another important aspect affecting the rate of adoption is how compatible the idea is to the particular situation of a potential adopter, their cultural values, past experiences or previously adopted ideas; putting each respondent on a continuum, ranging from low to high compatibility with regard to this particular innovation.

Respondent 1 explains that they chose to trial Kernza because of their interest in the dual-use nature of the crop [food and forage production in one crop] as well as its breeding potential, two aspects they appear to value a lot in their role as a researcher. This farmer was capable of sowing the crop successfully, openly presenting descriptions of how it can be done;

in practice showing that the innovation was compatible in terms of previous experience, and previously adopted ideas.

In comparison, respondent 2, who primarily trialed the crop to help researchers, but also to see how well it would compete against the giant ragweed infestation at their farm, had very different motives. Their values appear to revolve more around finding organic methods to solve a weed-problem, where perennial crops presented themselves as a potential solution. In this case, previously adopted innovations and experiences may have decreased compatibility, as the farmer had already found a crop [annual hybrid rye] that appeared to alleviate some of their problems while carrying less uncertainty than the perennial crop, which the farmer had much less experience growing.

For respondent 3, the appeal of Kernza revolved a lot more around its environmental impact, and economic potential resulting from less soil cultivation. This farmer highlights the importance of economic sustainability, stating that at current, the yield of Kernza is too low if it is being grown on fertile soils that could generate large harvests if planted with annual crops instead. These sentiments reveal a complex set of values, spanning from the desire to implement more sustainable cropping systems, while also valuing profits. These, previously adopted innovations, should they be preferred by the respondent, could also decrease compatibility, even though the farmer in question has enough experience to grow the crop successfully.

In the case of respondent 4, the circumstances are slightly more complicated. This farmer primarily focuses on grass seed production – an extremely intensive process involving heavy use of both fertilizers and pesticides, who explicitly says that they want to move away from lawns, and more into the realm of food to create a more positive impact. But this producer, for the time being, is locked within their own production system, previously adopted crops, and systems of seed quality necessitated by the seed industry. This can be interpreted as the values being in line with growing perennial crops – and that the experiences [and machinery] necessary to do so successfully is already in place – but that the current production system may not be completely compatible. Depending upon the needs of the industry [if there is a demand for conventionally produced Kernza seeds], these variables will affect whether or not the grower will continue growing the crop and scaling it up.

Respondent 5, in comparison, who has worked with perennials for a very long time, developing close relationships with various research organizations, is very open-minded about their thoughts to reshape their agroecosystem to accommodate plants that rebuilds soil organic matter and contributes with other ecosystem services. In this instance, the values, experiences and previously adopted innovations appear to make the farmer very compatible with Kernza and other perennial crops, the latter of which they express a very large interest in.

6 Results Part II: Potential Benefits in Perennial Grains

6.1 Arbuscular Mycorrhizal Fungi under Annual and Perennial Grains

The secondary objective of the thesis has been to investigate the abundance of PLFA and NLFA 16:1 ω 5 in the soils of four different agroecosystems. The results from the PLFA analysis did not show any significant differences of PLFA 16:1 ω 5 between the different agroecosystems, either at a depth of 0-5 cm or at 5-30 cm. The data did not show any detectable values at depths 30-60 and 60-90 cm. But in the analysis comparing the abundance of the equivalent NLFA in the different agroecosystems, the NLFA 16:1 ω 5 was found to be more abundant at 30-60 cm in the three-year Kernza than in the other agroecosystems ($F=30,042$, $df=3$, $p<0.05$). No significant differences were found at the remaining depths, but a potential tendency ($p=0.073$) is detected at 0-5 cm in the three-year Kernza, where NLFA 16:1 ω 5 is $p<0.1$ (Fig. 2).

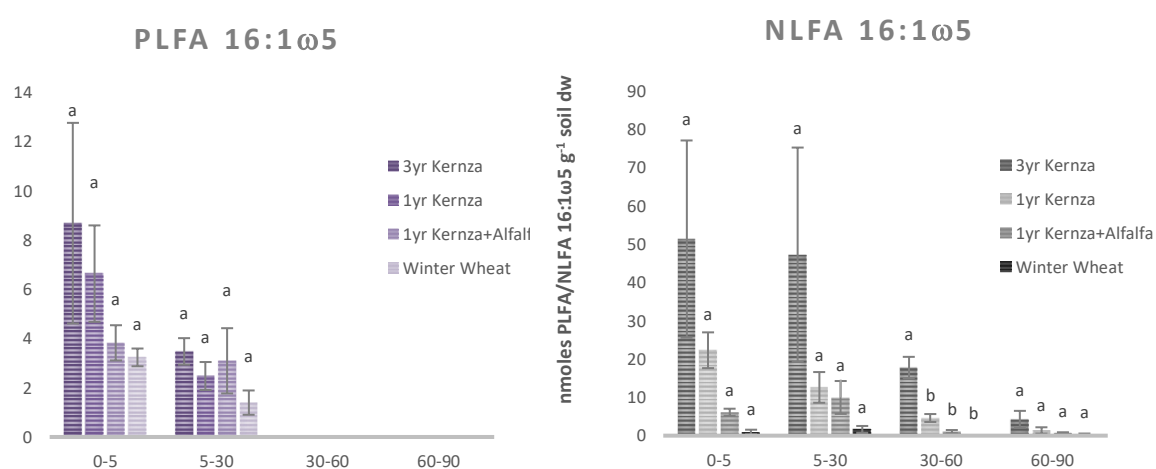


Figure 2. Comparison of the abundance of NLFA and PLFA 16:1 ω 5 in the four different treatments expressed as nmol g⁻¹ soil dry weight at different soil depths. Each bar represents the mean value of four replicates in each treatment, while the error bars indicates the standard error. Letters a to b denotes the significant difference, if there is any, between the treatments within each depth. No values were detected at depths 30-60 and 60-90 cm in the PLFA analysis

When comparing abundance of PLFA 16:1 ω 5 at different depths within the agroecosystems, there were significantly higher levels of PLFA 16:1 ω 5 at the depth 0-5 cm compared to depth 5-30 cm in the winter wheat treatment ($F=1.162$, $df=5$, $p<0.05$), see Fig. 3.

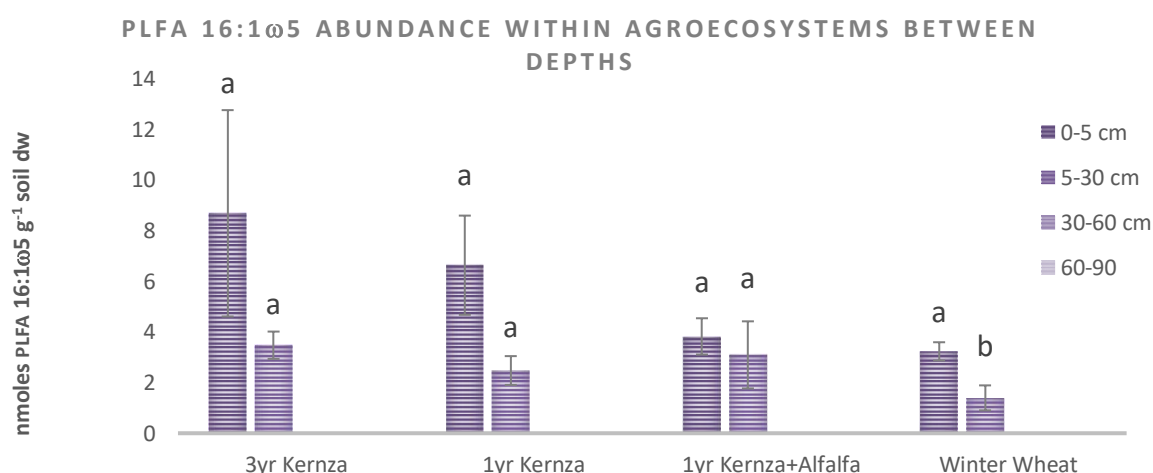


Figure 3. Abundance of PLFA 16:1 ω 5 in the four different treatments expressed as nmol g⁻¹ soil dry weight at different soil depths. Each bar represents the mean value of four replicates in each treatment, while the error bars indicates the standard error. Letters a to b denotes the significant difference, if there is any, within the treatments and between each depth. No values were detected at depths 30-60 and 60-90 cm.

The abundance of NLFA 16:1 ω 5 did not differ between depths in the three-year Kernza treatment, while it was significantly higher at a depth of 0-5 cm, intermediate at depths 5-30 cm, meaning that it did not differentiate from the other depths, and lower at depths 30-60 and 60-90 cm in the 1-year Kernza plots ($F=8.798$, $df=3$, $p<0.05$). This pattern is somewhat repeating in the 1-year Kernza intercrop with lucerne, where a higher abundance can be seen at depths 5-30 cm than in both 30-60 and 60-90 cm ($F=4.035$, $df=3$, $p<0.05$), whereas the top-layer does not differ from the other layers. The treatment with winter wheat did not show any significant differences between depths, exhibiting very low values at all measured depths (Fig. 4).

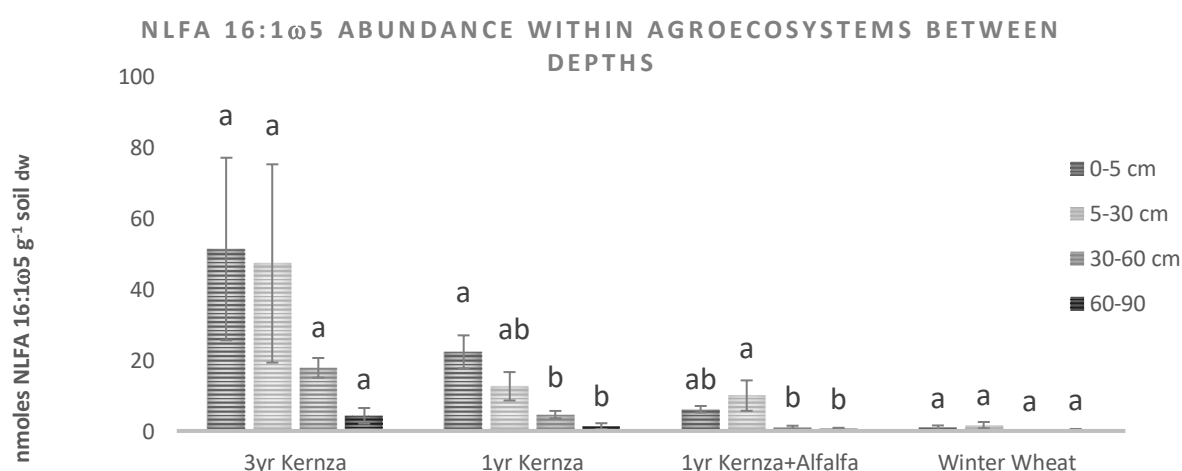


Figure 4. Abundance of NLFA 16:1 ω 5 in the four different treatments expressed as nmol g⁻¹ soil dry weight at different soil depths. Each bar represents the mean value of four replicates in each treatment, while the error bars indicates the standard error. Letters a to b denotes the significant difference, if there is any, within the treatments and between each depth.

7 Discussion

7.1 Experimenting with Perennial Grains – Farmers Motivations

This part of the thesis aimed to answer what fundamental motivations guide farmers to experiment with novel crops like Kernza. The results reveal multiple reasons as to why these crops were interesting to farmers, ranging from very specific on-farm needs to more general motivations. These include the desire to plant more sustainable crops, earn profits from seed production, assisting researchers and TLI with trials, or satiating the respondent's curiosity – an important motivation for all the respondents in the group.

Although limited by the number of participants in the study, the results show that the farmers growing these crops come from a wide variety of backgrounds, with different values, skillsets, and different outlooks on the future. This heterogeneity in backgrounds mirrors the heterogeneity in motivations highlighted by the farmers themselves. What is missing is farmers who grow the crop because of its qualities as a product, future promises of reduced maintenance and resource use. This can be explained by the fact that the crops are being grown at a relatively modest scale, and that issues in production, including harvest and yield are still fluctuating a lot; issues highlighting just how early in the development process Kernza actually is.

That said, the present study highlights a lot of potential in some of the growers, who early on expressed interest in trialing other innovations (i.e. other perennial crops, and mixtures thereof): motivations that may become increasingly important to uphold as TLI moves towards the market with other agroecological innovations. These motivations, together with the motivations among several members of the group to support the mission of TLI is an essential resource to the institute in terms of opening doors to new networks of potential adopters and research partners, trialing new crops, and getting site-specific and real world data on crop- and ecosystem performance.

7.2 Perennial Grains Through an Innovation Framework

Perennial grains, in this case exemplified by Kernza represents a new and innovative pathway towards a more sustainable food system. But the crop itself is still a work in progress, as evident by the present interview study, or in the words of The Land Institute itself (The Land Institute 2019a). Given this situation, to discuss the diffusion and adoption of Kernza both in the US and globally may seem premature. While a future version of Kernza may benefit farmers by yielding at a level that approaches wheat for several years without replanting, reduce tractor hours, fertilizer use (if intercropped) and other inputs, the current crop cannot reliably deliver on the above at a satisfactory level at this time. Although research and development is progressing fast (Zhang *et al.* 2016), a more in-depth diffusion/adoption study of perennial grains is still some years away. This study has therefore focused more on the *proto crop* Kernza, which already delivers on promises such as forage- and small-scale seed production on marginal lands; leaving the opportunity to study the “ideotype” of Kernza – i.e. the “final” version of the crop to other researchers in the near future. This distinction is important, because it differentiates between the current innovation of Kernza, and its future iteration – two potential products with very different relative advantages and challenges. But so far, this ideotype remains at the idea stage – hinging upon advancements in research and breeding that reduce the yield decline of Kernza after three years, breeding to remove problems such as shattering, and continued strides forward in terms of yield increases.

To better understand the diffusion of this *proto crop* on the market, and its implications for future perennial crops, the discussion has focused primarily on the relative advantage complexity, trialability, observability, and compatibility for the farmers currently using it.

Relative Advantage

The results highlight that several of the farmers motivated their choice to experiment with Kernza because of its sustainability profile and its future potential, where the choice to plant the crop drew mostly on the curiosity of the respondents. This curiosity may have been sparked by research and marketing showing the potential of Kernza to rebuild soil and even reverse climate change. Such visions will inevitably attract interest among innovators and early adopters of new ideas. These advantages may be very strong among end-users, who may choose to buy the grain at a premium price, in part because of its ecosystem services, in part because of its unique qualities as a food. But the advantages highlighted by the farmers in the present study revolved around the dual-purpose capabilities of the crop, its potential to generate an income from marginal lands, or its long-term capacity to restore soil, which is consistent with previous research performed *ex ante* by Adebiyi *et al.* (2016) and Marquardt *et al.* (2016) and *ex post* by Lanker *et al.* (2019). While these insights are not particularly new, as evidenced by past and ongoing research on for example dual-purpose systems with Kernza and livestock (Pugliese *et al.* 2019) – using them to develop a diffusion strategy might constitute a new approach going forward.

If these advantages could be quantified in economic terms, and made easily available to parties interested in growing Kernza, they could very well be a steppingstone for farmers to learn about and use the crop until such a time where overall crop performance, and especially seed yield is more consistent. Given that this crop could be grown on marginal lands, the relative soil-building and revenue-generating benefits of the crop should also appeal both to farmers and organizations responsible for environmental protection – organizations that may also be able to allocate funding towards protecting waterways or other sensitive habitats, or by subsidizing perennial grains on terrain prone to erosion.

Incentives have been shown to increase the adoption of new ideas, especially among individuals and companies who may not otherwise have taken the leap because of socio-economic constraints (Rogers 2003). On the other hand, incentives could also decrease the quality of adopters, leading to individuals and companies adopting the idea temporarily just to gain access to the incentive. That said, incentives could play a vital role in the roll-out of perennial grains, as noted by the respondents^{R1}, especially considering that some of the advantages only reveal themselves after a long time. This type of innovation is often referred to as a *preventive innovation*, where adoption reduces risk long term (e.g. soil loss and nutrient leaching), or where the benefits of adoption is not immediately rewarded to the adopter. This makes it complicated for potential users to perceive the relative advantage of a new idea, which in turn reduces its likelihood of being adopted, or its diffusion speed – a case where incentives could make a difference; along with more in-depth knowledge of what to expect from the crop at this point in time.

Other groups might perceive the relative advantage of these crops with more ease. These may include perennial seed producers who already have the know-how and machine park capable of growing perennial plants, or producers who already work with niche crops, and thus, might be more interested in innovation, as well as farmers who work with integrated crop-livestock systems in areas with a lot of marginal land. A commonality among all of these

potential adopters is the need for understanding the basic economics of how annual and perennial cropping systems compare over time, which will become increasingly important as the crop approaches a wide market release. This is especially important when considering that this particular variable is one of the strongest predictors of the rate of adoption of a new idea (Rogers 2003).

Complexity

Incorporating Kernza into the daily operations of a farm presents several challenges highlighted by the respondents. When problems arise, the farmers most often reach out to the contact that supplied them with seed, alternatively find a solution on their own. Given how young the crop still is, advice from extension agents is largely non-existent; what exists is the expertise of the farmers themselves, and the research institutions and marketing agents that supply farmers with seed – a knowledge base that is in constant flux, with new findings that shift advice from one day to the other. Apart from this, TLI also has a very extensive guide on how to grow Kernza on their homepage (The Land Institute, 2019c), but this guide is based on US Agriculture in the Upper Midwest, which does not always translate well into other areas of the country – or other countries of the world, where the crop is now slowly making an entrance.

Despite this, all the respondents found ways to tackle this complexity, finding solutions that fit at their particular farms – although some farmers argue it to be more complex than the rest of the group. For these farmers, having access to the networks above may have reduced the complexity of growing the crop substantially, but another explanation might relate to the theory of innovation; that most of the farmers in this group are simply more innovative than other would-be adopters, for whom this complexity may be a barrier to adoption (Rogers 2003). But on the other hand, complexity can be relative: for farmers who have prior knowledge of perennial seed production, and even the machine park in place to grow these types of crops, growing Kernza might be relatively straight forward. For this reason, the complexity of growing Kernza is very context dependent. But it also means that innovators with the right circumstances, i.e. knowledge, necessary machine park and resources to absorb potential financial losses, could experiment with and develop knowledge of this crop in their local settings today. This knowledge may be invaluable if shared with other potential adopters, and extension offices that want to learn more about the crop before it is completely ready for a mass market release – a role in which the innovator may act as a gatekeeper, normalizing unfamiliar ideas in their respective networks (Rogers 2003). By sharing this information, the innovator may reduce the complexity of the crop, which in turn may reduce the uncertainty felt by other growers. Coupled with the translation of TLI's guide to other languages, with research and knowledge added from different countries, these actions could increase the likelihood of Kernza adoption in the future, both in the US and in international markets.

Trialability

The opportunity to actually trial a crop like Kernza constitutes another door opener for future potential growers to reduce their uncertainty about the crop, to better understand its relative advantages and to see how well it may function at each individual growers' farm (Rogers 2003). At the moment these trials are closed, only open to farmers who sign agreements with, and enter into collaborations with TLI and its partners. However, at present, the point of these trials is not to reduce uncertainty, but rather to increase the test area, and to receive feedback

from farmers. This generates new knowledge among the users, highlighting some of the crops' current limitations and state of development, but also allows them to be a part of the knowledge creation process as they trial how different machinery could be used to plant, maintain and harvest it. As the crop and its best practices continue to develop, this knowledge could become essential to new groups of producers looking to adopt the crop in the future; reducing the need for further extensive trials prior to adoption, which in turn could potentially increase the rate of adoption (Rogers 2003). However, as the crop now moves closer to market, with more large scale plantings replacing the relatively small test plots, uncertainty and risk increases, which places extra demands on the ability to trial the crop in a way that generates meaningful insights. While this may no longer be a problem, some of the farmers in this study were so keen on planting the crop, they decided to plant it outside of the recommended seeding window when their seed deliveries were delayed. This may have had negative consequences for the crop, and in turn, negatively affected the growers perception of it. But similar problems may also arise when growers skip small-medium scale trials to grow the crop on large areas directly, especially if the harvest fails. This may be circumvented by forcing new growers to first trial the crop on a more modest scale, before scaling up production – especially when the crop is to be grown in a new area, where knowledge about its suitability is limited. Such trials may open the door to new test areas, giving the farmers in a particular region the opportunity to observe the crop as it is being trialed in their vicinity – increasing interest and long term adoption; but it may also reduce interest, if the test areas are too large and the crop fails (Rogers 2003).

Observability

The results show that several of the farmers in the study accept farm visits, interviews or take part in communicating their work with Kernza in one form or another. Whether the farmers themselves visited other growers or TLI before adopting the crop remains unclear; a result of the theory being applied after the interviews had already taken place. These farms play an increasingly important role in showcasing Kernza to future adopters, who may both want to observe it in practice, as well as trial it before moving forward with the decision to adopt it (Rogers 2003). This translates into a need to make information about the crop as readily available as possible, especially in use-cases where the crop might find a place in an agroecosystem already; on marginal lands, and where the farmer may use the entirety of the plant – both its seed and forage. Examples of farmers doing this and actually measuring the environmental and socio-economic effects could become perfect examples for future adopters to learn about the crop.

Other opportunities to increase observability include the annual prairie festival at TLI, where different stakeholders in the value chain gets an opportunity to see the crop, understand its relative advantages and current limitations, and perhaps even partner with farmers to trial, and eventually scale the crop when the time is right. These opportunities to share knowledge about Kernza in-depth can be very valuable, especially considering the crops' current limitations; issues that may be hard to communicate in other channels. This approach has been very successful for TLI, as evident by their current collaborations with Patagonia Provisions, who produced the “Long Root Ale” beer made with Kernza, or the limited-edition cereals by Cascadian Farms (The Land Institute 2019a).

Compatibility

For Kernza to become an appealing option for growers in the future, all of the above variables are important. But the compatibility of the product with the potential adopter is just as essential. The respondents in this study highlight a large variety of needs, cultural values, experiences, and previously adopted innovations – such as various components in their current farming operations; grass seed equipment, small grain equipment, animals, or large scale machinery. In most of the presented cases, compatibility was relatively high, as most farmers had found a solution, with or within the crop to an existing need, leveraged past experiences and found ways to incorporate the plant on the farm, at least temporarily. But in order for the farmers to continue with the crop long term, finding a place within the crop rotation is seen as problematic, at least by farmers with little knowledge of perennial plants, while other respondents humbly highlight the low yield of the crop as barrier. This is important to highlight, especially when a crop like Kernza might not reveal its economic benefits as quickly as an annual crop, which puts it at an disadvantage. Altogether, this highlights the complex nature of innovation diffusion and adoption, but it also reveals potential pathways forward.

When faced with the choice to adopt an idea, Rogers (2003) states that the potential adopter will use their past experiences as a mental tool, comparing new ideas with those already adopted. This means that ideas that are similar to the ones that are already in use, are more likely to be successfully adopted. When launching a new crop like Kernza, this might translate into a strategy whereby farmers who for example grow perennial grass seeds or small grains organically may be identified and chosen to trial the crop – farmers who may or may not also have animals to make use of the feed. Another way forward could be to find farmers in transition to organic production with a lot of marginal land, or farmers who could theoretically replace their long leys with perennial grains. These suggestions draw upon the answers from the respondents in this study, who appear to have been attracted to the crop because they happened to have previous experience in these fields, or having invested a lot of resources into the tools that seem to work with perennial grains.

These “stereotypic” or model farmers might not find Kernza as revolutionary as someone lacking these experiences or tools. But these innovators could open the door for other growers, popularizing and normalizing the crop in new networks. These farmers represent an interesting steppingstone for launching new perennial grains to growers who already have a lot of experience with other perennials – and in extent, are much more likely to adopt new and similar ideas. Such growers could over time be introduced to intercropping practices, if those are not already being practiced, which in effect would open the door to the long-term vision of TLI – introducing perennial polycultures as a means to achieving ecological intensification (Crews *et al.* 2016).

7.3 From Product Innovations to Systems Innovations

While Kernza can be seen as a product innovation per Tidd *et al.* (2005), it may also be seen as a process innovation, changing the way agriculture is performed by for example radically limiting soil cultivation and inputs. But Kernza and other perennial grains, should they be successfully diffused on the market in the future, may become more than the sum of their parts. If perennial polycultures can be realized, they will radically shift our mental models

governing how we practice agriculture from an annual to a perennial model, in turn becoming a paradigm innovation.

The process of realizing this vision, and the idea of ecological intensification (Bommarco *et al.* 2013; Crews *et al.* 2016) will require changes to farmers agroecosystems at the systems level (Gliessman 2014), akin to the transition from conventional to organic agriculture as described by Padel (2001); a process ridden with complex decisions. According to innovation theory, such ideas will likely diffuse more slowly in the marketplace, especially if their relative advantages are hard to convey (Rogers 2003). In this case, innovation theory presents an interesting concept known as *technology clusters*, whereby a radical innovation is broken down into segments that are gradually diffused into the marketplace – building upon the idea described above: that ideas similar to the ones already adopted appear easier to diffuse (Rogers 2003).

Another way to accelerate adoption could be to work more closely with other perennial solutions that already exist, and to experiment with annual polycultures as well: the building-blocks of the weak perennial vision presented by (Smaje 2015b). Such systems could initially incorporate perennial grains that over time may grow in significance as the perennial *proto crops* are replaced by their realized “ideotypes.”

7.4 International Expansion: Lessons for Europe and Beyond

Over the past few years, Kernza has gone from being a crop grown on small test sites across the US into a crop that is being trialed on much larger acreages outside of the US, where the 26-hectare farm in southern Sweden represents one example (*Dagens Industri* 2019). The experiences shared by the respondents in this study, and the innovation framework applied to those experiences could act as an important guide to new growers, organizations and researchers around the world seeking to be a part of the transition towards perennial cropping systems that enable ecological intensification (Crews *et al.* 2016).

Our results show that Kernza is still very much a work in progress, but it also reveals that the crop could serve several important functions in agroecosystems today – even if seed yields are still relatively low (Culman *et al.* 2013) and unpredictable over time, decreasing with stand age (Jungers *et al.* 2017). This is especially true for farmers who could use the feed for forage, or who could get incentives for growing a perennial on marginal land prone to erosion and leaching; where the seed yield could be an added benefit, which given the proper cleaning and sorting facilities, could be absorbed by innovative food companies relatively quickly. From a Swedish perspective, growing it on a larger scale may work after necessary trials have been conducted to see how it fares in a new environment, in which case the grower or food company need to be aware of the inherent risks of the crop. If such a course is pursued, TLI has a comprehensive guide on how to grow the crop on their homepage (The Land Institute 2019c) – a guide which should be complemented by contacts with growers and organizations who have already trialed the crop in Sweden, i.e. SITES Lönnstorp at SLU Alnarp (SLU, 2018c), Hånsta Östergårde (Solmacc, 2019) and Högestad Gods (Högesta, 2019); along with lessons from this thesis and the work by (Lanker *et al.* 2019).

Viewed from a broader perspective, these trials should be complemented with one or several organizations that take responsibility for the development and maintenance of perennial crops in a particular area or country, much like TLI does in the US – or at the very least, by establishing or including an organization that functions similarly to Plovgh. In the US, both of these organizations are a part of even larger collaborations between research and

industry, with stakeholders from the whole value chain. Taking Kernza to market has required that these transdisciplinary partnerships exist. These collaborations could take on many shapes, but they are especially apparent during the annual US Kernza conference organized by TLI, where most of the stakeholders in the value chain are present, including small-scale pasta- and beer makers, cafés and restaurants, or even larger companies such as Patagonia Provisions and Cascadian Farms who develop new products using the grain. This conference usually revolves around sharing the latest research and development of Kernza, focusing on several aspects of the crop, i.e. crop breeding, ecology, agronomy and market development. But it also features workshops and round-table discussions where these groups get to interact and discuss problems and solutions across traditional boundaries to facilitate quick progress.

These actors and processes could inform similar structures in other countries, to ensure that these crops are continuously developed to fit into their local contexts, developing and spreading advice among extension offices, and over time, developing the market by including large food companies that, much like in the US, decide to bear the risk of production by paying the grower per hectare rather than per ton (Lanker *et al.* 2019). These efforts could be supplemented by farmer networks, where information can flow more freely between stakeholders. If this knowledge can be stored and shared between umbrella-organizations from different countries, these crops could potentially see a relatively rapid progress and roll-out, which could act as a model for other perennial crops.

7.5 Potential Limitations and Errors

The study's respondents consisted of a group of five farmers who expressed interest in the study at the last minute. Having such a small sample was not ideal, but given the time allotted, had to suffice. The initial idea was to conduct interviews in the US, but because of complexities realizing this, interviews had to take place over the phone. The choice to use an innovation framework to analyze the results of the interview study came after the interviews had already been conducted, which limited the analysis in terms of what questions the respondents were asked.

In the analysis and discussion, a lot of weight was put onto the vision of realizing ecological intensification with perennial polycultures: an area with a lot of potential for pro-innovation bias, especially when considering that these crops and their potential agroecosystems still lay far in the future. But given the tremendous potential that these radical ideas exhibit, highlighting this potential may be considered justified.

7.6 Microbial Communities in Annual and Perennial Grains

Although not statistically significant in all the treatments, the results indicate several strong patterns in line with the first hypothesis: that the perennial agroecosystems generally seem to harbor more AMF (PLFA and NLFA 16:1ω5) than the annual system planted with winter wheat. This is in part supported by the increased levels of AMF at 0-5 and 30-60 cm in the three-year old Kernza system, which indicates a relationship between the abundance of AMF, agroecosystem and age. This relationship could be explained by a number of factors, where the time without disturbance, in combination with active plant roots could account for the abundance of AMF in the perennial agroecosystems. This is in line with previous research on reduced- and no-till agriculture (Kabir *et al.* 1997; van Groenigen *et al.* 2010) as well as studies on grasslands previously devoted to annual crop production (Allison *et al.* 2005) linking

reduced disturbance to increased levels of AMF; which in turn could explain the increased abundance in the oldest Kernza system relative to its two younger counterparts.

Inversely, high levels of soil disturbance, such as harrowing and tilling has been shown to be detrimental to AMF (Kabir *et al.* 1997), which would explain the low values detected in the winter wheat treatment. This system was exposed to harrowing and tilling up to six times before the winter wheat was planted, along with a full production cycle with non-mycorrhizal (Lambers *et al.* 2008) spring oilseed rape prior to planting. Together, these actions may have severely diminished the abundance of AMF in the winter wheat relative to the perennial systems.

But AMF abundance may also have been affected by the date of sampling, which occurred in late winter/early spring, when temperatures were low, and the winter wheat was only a few centimeters tall – a state of development which may be associated with lower levels of root colonization and activity of AMF in annuals (Abbott & Robson 1991). Research by Abbott & Robson (1991) indicates that AMF development and activity may be closely associated with the development of annual host plants, rapidly increasing during the growing season, and declining when roots senesce in the fall. In perennials however, this pattern appears to be different: exhibiting zero seasonal variation, as showed by Brundrett and Kendrick (1988), see (Kabir *et al.* 1997); highlighting the need for studies over a full year. That said, measuring the activity of AMF and its interactions with Kernza went beyond the scope of this thesis, which simply aimed to estimate AMF abundance.

The second hypothesis stated that there should be more AMF in the deeper soil layers of the perennial systems compared with wheat – with more fungi present in the three-year old Kernza, compared with both one-year old Kernza systems. This hypothesis is also in part proven correct, evident by the significantly higher levels of AMF NLFA 16:1 ω 5 at a soil depth of 30-60 cm, compared with the biomass in the other systems at the same depth. The increased abundance at these depths could be explained by the downward extension of Kernza's root system colonizing the soil profile down to 30-60 cm at a greater rate than in the other agroecosystems. This hypothesis leans on Sprunger (2015) who showed significantly higher levels of root biomass in another three-year old Kernza system down to 40 cm, as compared with wheat; and (Abbott & Robson 1991) who states that the development of AMF may be strongly associated with the host plants roots, at least in annuals.

But the lack of significant differences, and the absence of detectable values at depths 30-60 and 60-90 cm in all PLFA 16:1 ω 5 analyses leaves room for speculation. These results could simply indicate that values were too low to be detected in the samples, but they may also be the result of errors in the sampling and analysis process, see further down.

The third hypothesis stipulated that the presence of a legume would stimulate the development of AMF in the Kernza and lucerne biculture, generating a higher biomass when compared with its sole-cropped counterpart. This hypothesis was disproven, as no significant differences between the agroecosystems could be found. This outcome could be due to the nutrient status in the soils sampled, or the fertilizer strategies employed at SITES Lönnstorp prior to the planting of the agroecosystem in question, where high P levels could discourage the formation of mycorrhizae, reducing the need for a tripartite symbiosis between the fungi, plant and BNF symbiont (Püschel *et al.* 2017). Other explanations could include competition at the root surface between both AM and BNF symbionts.

The overall lack of significant differences in some of the results may be due to the high variance in the soils sampled, which exhibited several spots with a very high clay content and

a crumbly structure randomly intermixed. But the variance could also stem from errors made after the sampling process, when the soil cores were mistakenly frozen before mixing and sieving, complicating the process of homogenization. These issues were further compounded by the high water content in the clay-rich cores, which made it difficult to break them into small enough pieces to sieve and mix according to protocol (Frostegård & Bååth 1996).

On the other hand, the results could also have been affected by the ecosystems themselves and the life history of AMF – whose spores can persist for a long time in soil, indicating that their presence may reflect the sporulation history of a particular soil, rather than show the current state of symbiosis (Hijri *et al.* 2006). Meanwhile the management practices could also have affected the abundance of AMF, such as fungicides, herbicides and pesticides. In this case, no pesticides were applied in the perennial systems, while the annual winter wheat received several doses of both herbicides and insecticides. No fungicides were applied during the growth of winter wheat, nor during its predecessor. No research could be found connecting these substances used to reductions in AMF, but research thus far has been limited. This may be due to the sheer amount of substances, varying dosage recommendations, agroecosystem variability and other factors, making it hard to determine the exact effects of these substances on AMF, which continues to yield ambiguous results in the few studies that have been conducted (Hage-Ahmed *et al.* 2019).

Taken together, the results indicate that AMF is present and more abundant at deeper soil layers in the perennial agroecosystems compared with their annual monologues. While this thesis is limited in scope to the abundance of these microorganisms, it could be speculated that all crops studied interact with AMF at a varying degree; interactions that have been shown to increase both crop and agroecosystem performance, simultaneously reducing the need for external inputs like fertilizers. Whether a higher abundance of AMF in this case equals more activity or a higher diversity of these fungi remains to be seen, as does the potential effects on the agroecosystem as a whole. These processes need to be better understood, which warrants more research on the topics described above, as well as more context-specific research, such as the effects of domestication and breeding on AMF responsiveness in future plants. Even if a majority of land plants have the ability to enter into symbiosis with AMF (Hodge 2000; van der Heijden 2010), no research has so far focused on the interactions between Kernza and AMF to determine the extent to which these organisms exchange resources, how colonization takes place, or the potential benefits to the plant and agroecosystem as whole – which also highlights the need for further scientific inquiry.

7.7 Potential Limitations and Errors

The results show a very high variance in some of the samples, especially apparent in the upper soil layers (0-5 and 5-30 cm) in the three-year Kernza plots. Whether this variance was natural or not is speculative, but it may have been affected by the method employed, and in particular the soil conditions during sampling; where samples were mistakenly frozen before mixing and sieving, and sub-optimally broken to pieces, as already described. During the fatty acid analysis, another potential problem arose when a few samples accidentally received a higher concentration of KOH, which later received a second round of acetic acid to remediate the error. The last potential problem pertained to the GC analysis; where we should have used more soil in the extraction of the NLFA and PLFAs or dissolved the acids in less amount of hexane to improve detection in the samples.

Meanwhile, the strongest limitation in the PLFA and NLFA analysis includes the combination of two different field experiments: SAFE and the three-year old Kernza experiment. These were set up and configured at two different scales, where the three-year old Kernza was significantly smaller in terms of plot size compared to the systems in SAFE. But both systems also differed in terms of replication: where the three-year old Kernza field consisted of a long strip that was divided into four pseudo replications. Despite this being the case, the use of the three-year old Kernza experiment yielded interesting results that warrant continued research, by for example repeating the experiment, comparing the results from the now 3+ year old Kernza fields in SAFE with historical analyses from the same sites.

7.8 General Discussion

The emergence of perennial grains signifies several important advancements in the field of sustainable food production. Viewed through an innovation framework and applying the concepts of agroecology, systems thinking and ecological intensification, these crops, and the organizations developing them, could be categorized as radical innovations/innovators (Adebiyi *et al.* 2016) who open the door to a whole new way of farming – offering pathways to redesign agroecosystems from the ground up.

This approach differs from the rest of the industry in a number of ways. While new innovations in agriculture come into being on a regular basis, these most often focus on increased efficiency of the systems in place, incrementally making the agroecosystems perform better over time, but not solving some of the fundamental problems, such as erosion (Montgomery 2007). In the sustainability grading framework developed by Gliessman (2014), these practices/innovations can be categorized on levels 1-3 depending upon whether they merely increase the efficiency of the current industrial food system, as in the case of level 1, focus more in input substitution (level 2) or employ the idea of agroecosystem redesign to become more sustainable (level 3). Using this framework, it may be argued that Kernza opens the door to the redesign of agroecosystems to function more in line with natural ecosystems, much like other practices such as agroforestry does (Gliessman 2014). These innovations could go hand in hand with innovations within the field of soil ecology, where specific microbial communities could be paired with the right types of plants to restore or boost the overall health of an ecosystem (Chaparro *et al.* 2012; Koziol & Bever 2017), both below and above ground. These ideas are becoming increasingly popular as the fundamental concepts of soil preservation is becoming more and more important, evident by the rise in interest of no-till agriculture and similar approaches (Derpsch *et al.* 2010; Llewellyn *et al.* 2012), including the results in this thesis.

But Gliessman's (2014) levels of conversion continue past level 3 through 5; where level 4 constitutes a reestablished connection between producer and eater. On this level, it may be argued that the proponents of perennial cropping systems, i.e. The Land Institute, Patagonia Provisions and Cascadian Farms act as key door openers in their pursuit to develop and conduct research on perennial grains. This is made possible through the development of new food products, such as the Long Root Ale from Patagonia Provisions, or the cereals developed by Cascadian Farms; both of which use clever marketing campaigns to give consumers an opportunity to vote on the transition towards perennial cropping systems with their own money. Although the direct connection between farmers and eaters may be rare, the partnerships between these organizations, and their communication efforts have been very

successful at telling their story; engaging people to learn more, and to support the efforts being made to develop and grow perennial crops.

All of this is made possible through The Land Institute. Whereas many other organizations and companies work with incremental improvements, asking “how can we do what we do better”, or “are we doing things right”, organizations such as TLI have gone to the root of the problem, employing systems thinking when asking “are we doing the right things?” Over time, this mindset gave birth to research focusing on ecological intensification, a concept where perennial grains open the door to production systems that require less disturbance, moving the ecosystem further down the successional gradient. This mindset of working with the root cause of problems in agriculture to develop a product that solves many problems at the same time marks a radical shift in thinking, giving rise to ideas that can be turned into new products (crops, processed foods), and new processes (food production with less machinery, tractor-hours, seeds and fertilizers), to name a few.

These ideas may long term pave way for a whole new paradigm of thinking, a class of innovation that shifts our mental models completely, opening the door to a new food system where the standard way of producing food may be radically different than it is today. But this will require a roll-out of many different “level 3” innovations, most of which are still very early in their development process, and in need of more research to mature. These insights may be significant to the agroecological community, as they represent a way to incorporate agroecology at the farm level by use of new and more sustainable crops.

From a global perspective, these results highlight the current challenges associated with growing perennial grains, but they also show the potential of using it in a similar way it is being used in the US in places such as Sweden. If more farmers start to experiment with the crop, these could potentially collaborate with researchers in developing the best agronomic practices for the crop in a Swedish setting – knowledge that could be synthesized into handbooks and guides. For society, results herein indicate that perennial crops are developing fast, as is the interest in their ecosystem services and the savory qualities they carry. Now more than ever, people want to consume products that do well in the world, such as products like the Long Root Ale. This connection could prove to be a key enabler for more research into the development of perennial grains – if consumers could buy products that directly sponsor these types of organizations and their research.

But growing and selling the crop at this stage does not necessarily need to be very complex. Farmers could also choose to sell directly to small millers or specialty crop retailers, start their own online shops or employ similar tactics, if the necessary equipment to clean, de-hull and package the crops can be sorted out. This could work very well in countries like Sweden, where several companies have been very successful at selling niche crops in short value chains or directly to consumers online; Warbro Kvarn (Warbro Mill) who sells heritage grains like einkorn wheat, emmer and similar crops, or Nordisk Råvara, who buys and sells innovative and heritage crops like lupin, quinoa or lentils, produced in Sweden.

Future innovation/diffusion research should pick up during the final stages of Kernza/other perennial grain development, when the crops’ yields have stabilized at an adequate level for seed production, following the release and diffusion/adoption process of said crops on the wider market. But they could also follow the release of the crop as a soil remediation innovation, or a feed/seed innovation for marginal lands – a context in which it may thrive already. Such research could lead to new ways of diffusing similar innovations on the market, by for example developing agronomic guides relevant to other contexts than the US.

On the microbial side, this thesis marks a first on Kernza, where the abundance of AMF was studied in four different agroecosystems and at different depths. It reveals interesting trends in terms of soil colonization by AMF in perennial agroecosystems, but fails at determining what organisms constitute these groups, how active they are, and how they affect the plant community, whose soils they inhabit. These topics, along with research on the interactions of mycorrhizae and nitrogen fixating bacteria in perennial cropping systems could serve as an interesting research focus moving forward.

8 Conclusions

It is concluded that Kernza is a crop in development, acting as one of the primary examples of breeding efforts within the area of perennial grains. The crop is currently being trailed by a relatively small group of farmers, a few of which were included in the interview study in this thesis. These respondents were primarily motivated by and interested in innovation and sustainability, but the results also reveal that the attributes affecting the diffusion of new innovations like Kernza primarily revolve around the products' relative advantage, and the complexity of growing the crop in question. While the long-term potential of Kernza may include several economic or soil-building benefits, these benefits are not directly highlighted by the subjects in the interviews. The respondents instead highlight the possibility to employ the dual-use nature of the crop, to produce both seeds and feed for animals; a tactic which could be combined with growing the crop on marginal lands. This use case could open the door for relatively large scale Kernza plantings, on land where these specific needs are met – in turn growing the knowledge of the crops until such a time where the crop's seed production is high and stable enough for it to move beyond the *proto crop* or *beta stage*, enabling a wide-market release. These developments go hand in hand with a growing interest in sustainability and soil preservation practices such as conservation agriculture and no-till on practical side, and on the research side, a growing body of knowledge about how microbial communities may affect the farming systems in which they are embedded. A vast body of research shows that perennial plants sequester more carbon, reduce leaching and contribute with other ecosystem services compared with annuals; attributes that seem to carry over into domesticated or bred perennial crops, at least in the case of Kernza. This thesis is one of the first to show a higher abundance of mycorrhizal fungi in a domesticated perennial grain, as compared with a traditional annual wheat crop grown under similar conditions; but a lot of work remains to completely understand just how this may affect the farming systems in question. If development continues, perennial crops and their associated microbial communities have the potential to become paradigm-shifting innovations capable of changing how we view agriculture today, from systems where high yield is prioritized, to resilient systems where nature acts as the true measuring stick.

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